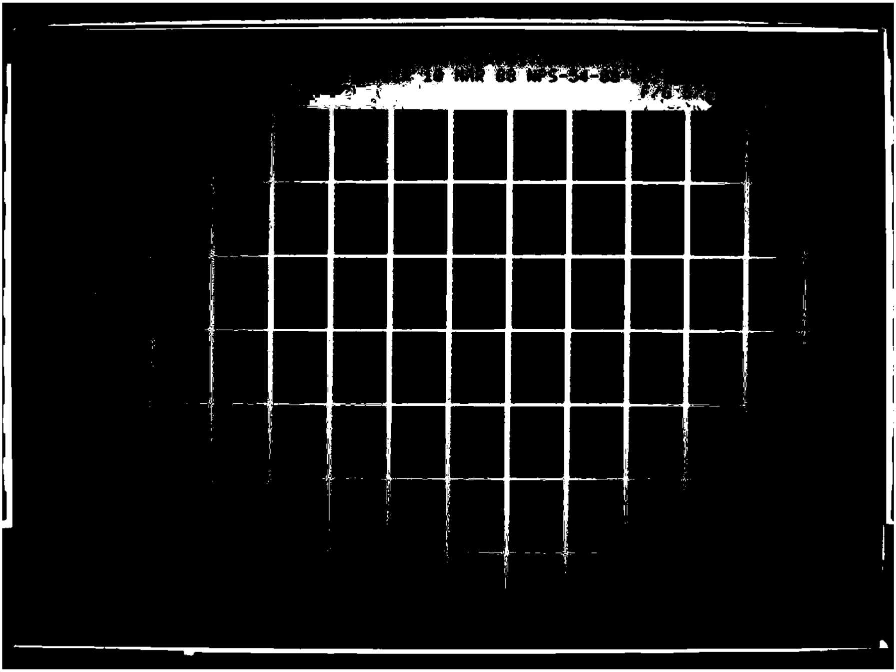
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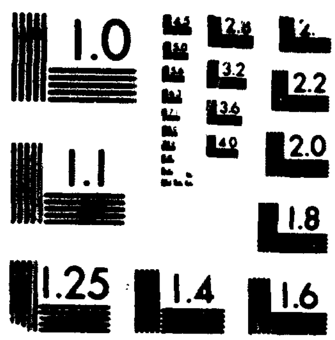

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

A METHOD FOR ESTIMATING AND CONTROLLING THE COST OF EXTENDING TECHNOLOGY

WILLIS R. GREER, JR.

March 1988

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Prepared for: Naval Sea Systems Command
Cost Estimating and Analysis Division
Washington, DC 20362

NAVAL POSTGRADUATE SCHOOL
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Both the theoretical and practical aspects of costing extensions of technology are addressed. A method for measuring the level of technology embodied in a system is developed. The increment in technology represented by a development project is found to be highly correlated with development time. Development time is then broken down into normal and abnormal components, which are found to be correlated with development cost. Cost control methods are developed.

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March 1988

PREFACE

This study was conducted at the request of the Naval Sea Systems Command's Cost Estimating and Analysis Division, Code 017. Funding was provided under the Naval Postgraduate School's direct funding allotment, Project Code N4P1. The objectives of this study were stated in the proposal document:

> Determine whether theory drawn from related disciplines holds promise for improving our understanding of how SOA [State-of-the-Art] extensions relate to development and production costs of military electronic components. If so, attempt to build a quantifiable relationship. (Note: the accomplishment of this objective will require specification of measurements for SOA extensions--to be drawn from measurement theory.)

This final report, along with copies of the data used, is submitted in fulfillment of the agreement. The report is releasable, but the supplementary data will be distributed only to DoD agencies by request.

The author wishes to thank several people who made this undertaking possible. Most notable among them were Michael Hammes (Director, 017), Jim Herd (now with NCA), Bill Broocke, Scott Endres and John Maurer. Finally, Captain Blain Webber (USAF) was especially helpful in providing and interpreting satellite data.

EXECUTIVE SUMMARY

When the various components of the Department of Defense (DoD) enter into contractual agreements calling for extensions of the State-of-the-Art (SOA), uncertainty generally requires that some variant of cost-plus contracting be employed. Therefore, it is important that DoD possess a highly developed ability to estimate the likely cost of achieving the desired technological advance.

This study began by examining the techniques currently available for costing SOA extension contracts by surveying the literature dealing explicitly with SOA measurement and costing. SOA measurement strategies usually employ regression to combine design variables in an effort to produce a single measure of the level of technology imbedded in a given system. The typical dependent variable is the "year of technology".

The relationship between the scale of an SOA extension and development cost has also been studied, but the findings from these studies have been disappointing. Cost estimates made early in the life of a project have been plagued with error. The focus of <u>this</u> study has therefore been to develop a cost estimating model that is demonstrably workable for both prediction and cost control uses.

In selecting the variables to be used to measure the technology embedded in a type of system to be studied, there is no substitute for expert judgement. Experts must bear in mind

that the variables selected must be influenced by the engineering development decisions. They should choose characteristics which are goals of the design process. In addition, the variables should be specified so that increasing values correspond to greater technical difficulty. Finally, the variable values should be ascertainable during the early decision-making stages of the system life-cycle.

In the present study 18 variables or composite variables that could be used to describe satellite technology were identified. There was unclouded discussion and the results obtained represented consensus.

A factor analysis was then run. In its final form, 11 of the 18 variables were factored. They clustered very nicely onto four factors with 81.7% of the variance explained.

The next step was to calculate factor scores for each of the 18 systems in the data set. Note that factor scores represent blends of parameters affecting the level of system technology.

The ellipsoid model was then used to determine the level of technology embodied in each satellite. This technology measure, the radial distance from the origin, is a second-order function of the four factor scores.

The end purpose of developing SOA measures is to facilitate prediction of the cost of developing new technological systems, which is a necessary initial step in any attempt to control such costs. The next step was therefore to search for statistical associations between (1) the degree to which a system's

technology is extended, and (2) the level of activity required to bring this extension about.

The technological objective of the project and the closest existing technology were used to identify the development task by referencing the technological distance separating the two. Several more detailed measurement concepts were then developed. The reach measures the total technological complexity, or the overall ambition of the project. Advance represents the "invention" aspects of the development--the "true" SOA progress required. The redesign portion represents a movement parallel to an old SOA surface.

The first hypothesis tested was that the difficulty of the development task, as measured by the time required for its completion, is a function of the three measures of technological spread. The result was,

Time = 52.86 +	218.93 Advance -	34.28 Redesign -	17.37 Reach	
t statistics	(3.69)	(1.45)	(0.47)	
Significance	.001	.085	.322	

Variance explained (R^2)	.791
Adjusted R^2	.728
Standard error of the estimate	8.745

The regression is highly significant. Advance is by far the most important determinant of development time. Neither redesign nor reach is statistically significant.

It was then hypothesized that development <u>cost</u> is not a smooth function of development time. If a program drags on beyond its intended completion date, it becomes relatively more costly to compress the required accomplishment into an increasingly abbreviated time horizon. This suggests that there is a "natural" project time, and that the <u>residuals</u> from this natural time may influence cost. Again, the multiple regression produced good results,

Cost = − 61357 + 4793.1 Predicted Time + 7391.4 Residual		
t statistics	(3.12)	(2.47)
Significance	.004	.013
Variance explained (R^2)		.590
Adjusted R^2		.516
Standard error of the estimate		82647

The most basic task in cost control is to explain variances between predicted and actual costs. The regressions provided a basis for doing so.

First, Advance, Redesign and Reach were used in the "Time" regression to predict the time that would be required for the system's development. Then the Predicted Time was input to the "Cost" regression (with the Residual <u>set to zero</u>) to provide an <u>ex ante</u> prediction of development cost.

Next the <u>actual</u> time for the project was compared to the predicted time to determine the Residual. The Cost regression

was then used again--this time to calculate a new cost estimate considering the residual time for the project. The difference between the ex ante cost estimate and the cost estimate based on the project's actual time is the "Variance Due to Time"--the portion of the total variance that can be attributed to the cost consequences of time delays.

Actual Cost is compared with the cost estimate based on actual time to determine a "Cost Control Variance". This variance indicates the quality of cost control for the project.

The fundamentals developed in this study provide a workable methodology for measuring the level of technology embodied in complex systems, and for measuring the degree of advance represented by the technological characteristics of new systems compared with old. This capability can provide information that may be useful for cost control.

The requisite data used in implementing this procedure have a great deal to do with the quality of the results achieved. If the benefits of good cost control are to be obtained it is absolutely essential to have a relevant and complete data base. It is necessary to have at least four valid observations (systems) in the data base for every factor that is identified through the factor analysis procedure.

The chief recommendation of this study is that DoD components who engage in technology-extension contracting carefully design and maintain high-quality data bases on systems that are likely to be targets for further development.

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Chapter 1

COSTING SOA EXTENSION CONTRACTS: A LITERATURE REVIEW

INTRODUCTION

Various components of the Department of Defense (DoD), including all the services, enter into contractual agreements calling for development of new technology, or for extensions of the State-of-the-Art (SOA). Occasionally the required development task can be sufficiently defined to allow use of a fixed price contract. More commonly, though, uncertainty requires that some variant of cost plus contracting be employed. In these circumstances the services must somehow estimate the likely cost of achieving the desired technological advance.

This chapter examines the techniques currently available for costing SOA extension contracts by surveying the more important literature dealing explicitly with SOA measurement and costing. The chapter then looks at SOA costing trends and discusses the new challenges that lie ahead.

Background

The cost of developing an SOA extension relates, presumably, to the scale of the undertaking. That is, it should be more costly to extend an existing SOA ten-fold than it would be to

make only a modest improvement. Therefore, the task of SOA cost estimating must be reducible to (1) measuring the degree of SOA extension represented by the contract and (2) establishing a relationship between degrees of extension and development cost.

Measuring levels of and extensions in SOA have been the subjects of much research. (The more important of these studies will be discussed in the next section.) The usual approach has been to identify a limited number of design variables or performance parameters that represent the overall level of technology embodied in the particular system or assembly under study. Examples might include: resolution power and size for sensor arrays; computational speed and memory size for computers; specific impulse and burn time for rocket motors.

Often there are potential trade-offs among performance variables within a particular SOA, such as with speed and useful load for aircraft. SOA assessment strategies frequently employ mathematical weighting techniques, such as regression, to combine design variables in an effort to produce a single measure of the SOA for a given system. One commonly (perhaps too commonly) used measure is the "year of technology".

The relationship between development cost and the scale of an SOA extension has also been extensively studied. However, findings from these studies have, for the most part, been disappointing. Cost estimates made early in the life of a project have been plagued with error. In the latter stages (when it may be too late to avoid heavy cost overruns) SOA extension

measures are usually irrelevant; the program is far enough along to allow more accurate bottom-up costing at a highly detailed level of the Work Breakdown Structure (WBS).

By chronologically examining the development of SOA extension cost estimating techniques, one can discern a pattern that may be useful in guiding the development of further improvements. Specifically, this analysis will suggest that the derivation of empirically based parametric models with somewhat more detailed input would produce superior results due to expansion of the relevant data base and to the infusion of additional methodological rigor. Thus our next challenge will be to prescribe a disciplined process for cost estimators to use in deriving appropriate models at the system, sub-system and component levels of the SOA extension.

COSTING LITERATURE

Literature on Measuring SOA

Dodson and Graver, 1969. While SOA has been measured using numerous methods for many years, Dodson and Graver reported an important theoretical advance in 1969.[1] Their innovation was to make use of convex (ellipsoidal) hypersurfaces to represent particular levels of SOA. In order to better understand the approach, consider that three steps must be taken:

1. An operational definition of SOA must be specified.

2. *N* SOA-determining parameters must be specified for the kinds of systems or subsystems under examination.

3. An *N*-dimensional ellipsoid must then be fit to the parameter measurements of an SOA-representative group of systems or subsystems.

Dodson and Graver addressed the first step by defining SOA as follows;

> In concept, SOA might be defined as the highest degree of technical accomplishment that could be achieved at any point in time. In practice, however, it would be impossible to reconstruct objectively what performance characteristics could have been realized at times in the past. On the other hand, performance and design characteristics that were achieved can be determined objectively. This suggests adoption of "state of the art" as defined by the physical and performance characteristics of development programs completed during the time period in question.[2]

Therefore, Dodson and Graver stipulate recently implemented technology as representing the current SOA.

Since no single measures of SOA have yet been developed, *N* SOA-determining parameters must be specified in such a way as to collectively describe the level of technology embodied in the kinds of systems or subsystems under examination. Dodson and Graver stated three guidelines to use in selecting parameters to represent SOA. First,

> The selection of SOA-determining characteristics should be concentrated on those that are at least partially influenced by engineering development decisions. The individual characteristics . . . represent constraints upon the achievement of other design characteristics which are--to a degree--goals of design.[3]

Second,

> . . . Characteristics should be specified so that increasing values of the characteristics correspond to greater technical difficulty.[4]

Finally,

> . . . The characteristics should be among those that are typically ascertainable during the early decision-making stages of the system life-cycle.[5]

This last guideline is particularly important if the final analytical output is to be useful when R&D funding decisions are being made, or at the early feasibility study stage.

Once the <u>N</u> SOA-determining parameters have been specified and measured across an appropriate sample, Dodson and Graver theorized that an SOA-describing ellipsoid could be fit to the data by minimizing squared proportional deviations (using scale free proportional measurements from the origin). The approach is best understood by envisioning the process in only two dimensions. (See Figure 1.1 on the next page.)

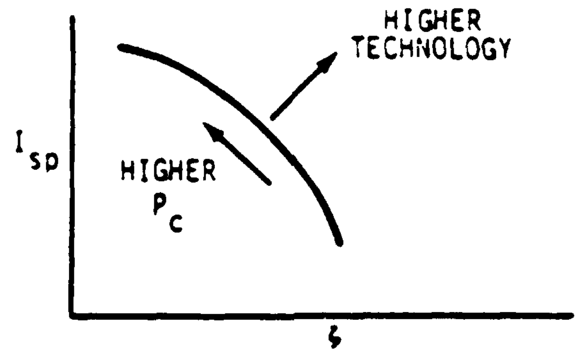

Figure 1.1 Dodson and Graver's Ellipsoid Approach

Two system attributes have been scaled on the two axes. The elliptical curve represents a particular level of technology or SOA. If mission requirements call for more of one attribute and less of another, the need could be met by moving along the curve. Note that SOA is <u>not</u> increased. Basically, the ellipsoid is an iso-SOA curve.

The SOA curve exhibits the economic property of diminishing returns. In order to obtain more of one attribute, ever-increasing quantities of the other must be given up. This is a common phenomenon in design.

Dodson and Graver argue that (in N-space) a new hypersurface is required for each SOA. The suggested inference is that the level of SOA advance embodied in a system with a particular set of attributes is the radial distance of the desired point from the most current ellipsoid.

<u>Dodson, 1970</u>. In 1970 Dodson published an oft-cited article reporting and expanding upon the results of his work

with Graver.6 In this article he went on to suggest that the ellipsoid model would be appropriate only when all system attributes approach finite upper bounds:

> When the dimensions include one or more terms which do not approach a finite upper bound, the form is planar. Thus, the choice depends upon the nature of the SOA-determining parameters.[7]

Next, he gathered data on seven missile propulsion subsystems with development completion dates between 1951 and 1955 and fit a four-dimensional, linear hypersurface to the data. The result is a simple equation defining the prevalent SOA during that time period:

$$\frac{X_1}{245.9} + \frac{X_2}{13.2} + \frac{X_3}{117.7} + \frac{X_4}{5.37} = 1$$

where X_1 = delivered specific impulse at sea level, in seconds

X_2 = propellant weight/total motor weight (including propellant)

X_3 = length-to-diameter ratio of motor case

X_4 = 1/burn time, in seconds.[8]

To test this model Dodson gathered additional data on a number of rocket motors developed between 1957 and 1961 and calculated SOA values for each using the same equation. Points representing subsequent systems were found to lie increasingly above the surface established for the 1951-55 time interval.

Alexander and Nelson, 1972. Alexander and Nelson's 1972 RAND report began by stating an important limitation to the

usefulness of quantitative models for measuring SOA. The limitation is that the progression of technology must conform to an assumption of "continuity";

> Continuity exists if two devices that appear at different times can be characterized by the same set of parameters. Continuity also requires that subsequent development can begin where prior development ended. . . . Basic research and invention are excluded from our purview . . . the output of such activity is unique, unpredictable, and unspecifiable.[9]

This important limitation qualifies the use of parametric SOA measurement models under evolutionary conditions exclusively.

Like Dodson, Alexander and Nelson theorize the existence of a curvilinear relationship among technological parameters. The following illustration demonstrates the posited association between thrust and weight for aircraft turbine engines. The curve labeled t_1 represents the level of technology existent at time 1. Technology characteristic of time 0 required more weight for an engine of equivalent thrust, while time 2 technology enabled an engine with the same thrust to be lighter. Note the diminishing returns, in terms of thrust, to increasing the weight of an engine. The design objective is lightness, of course: if we were to reverse the weight axis we would see a Dodson-like ellipsoidal shape.

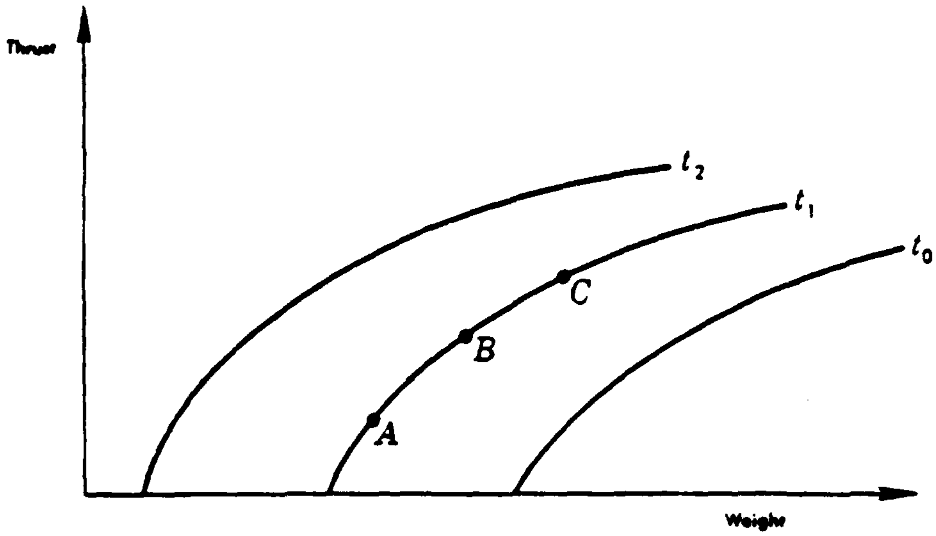

Figure 1.2 Alexander and Nelson's Turbine Engine Example

But, also like Dodson, Alexander and Nelson used linear methods to analyze their empirical data.

The general form of the model selected was,

$$t = F(P_1, \ldots, P_n)$$

where t is the point in time one would expect the described technology to appear and the P_is denote the performance parameters used to specify the technology.

Data describing 47 engines developed from the early 1940s to the late 1960s were subjected to analysis. The best results were produced by a semi-logarithmic form of the model,

$$\text{Tech} = -1187.5 + 156 \ln \text{Temp} + 18.8 \ln \text{Thrust} - 26.5 \ln \text{Weight} - 20.6 \ln \text{SFC} + 11.7 \ln Q + 13.0 \text{ Prop}$$

where,

Tech = Technology index; model qualification test date; quarters, 4th quarter 1942 equals one.

Temp = Turbine inlet temperature; Degrees Rankine.

Thrust = Military sea level static thrust; lb. or ESHP (equivalent static horsepower) if turboprop.

Weight = Engine weight; lb.

SFC = Specific fuel consumption at military sea level static thrust; (lb/hr)/lb thrust.

Q = Maximum dynamic pressure; lb/ft^2.

Prop = Dummy variable; one if turboprop, zero otherwise.[10]

The regression had an unadjusted R^2 of .903 and a standard error of 9.6 quarters. Alexander and Nelson expressed disappointment over the relatively large standard error saying, "The equation therefore cannot be used for making fine distinctions."[11] Nevertheless, they plot expected versus actual time and say,

> The 45° line is therefore defined as the average trend or expected date of technology over the period. Points plotted above the 45° line represent engines "ahead of their time": . . . points below the line are "late" or "conservative" developments.[12]

As an aside, there is an interesting section in the Alexander and Nelson report comparing the advance of U.S. jet engine technology with Soviet engines. They conclude the Soviets were ahead of the U.S. in the 1940s, but that the Soviet lead disappeared in the early 1950s. "Since that time the gap between the two technologies appears to have widened."[13] (With the U.S. pulling steadily ahead.)

Gordon and Munson, 1981. This paper made use of two general forms of SOA equations,

$$S = K_1V_1 + K_2V_2 + \ldots + K_nV_n \tag{1}$$

and,

$$S = V_1[K_2V_2 + K_3V_3 + \ldots + K_nV_n] \tag{2}$$

where S = State of the Art

K_i = A judgementally or statistically assigned weight

V_i = The value of the ith technology-describing variable expressed as a decimal fraction of the largest value of that variable in the data set.

The first version of the model, Equation 1, is familiar. The second version is a multiplicative form intended for use when one parameter must be present.[14]

There are two data-based examples in the Gordon and Munson paper. The first is an example of SOA measurement of a large sample of antibiotics using Equation 2, where,

V_1 = Minimum Inhibitory Concentration.

In this portion of the study the K_is were established, using subjective methods, by "the study team and its consultants."[15]

The second example used Equation 1 to study computers introduced to the market from 1951 through 1980. In the first part of this example the K_is were also established subjectively.[16] The variables were,

V_1 = Computer speed (operations/second)

V_2 = Cost of computation (operations/dollar)

V_3 = Maximum memory size (kilobytes)

$K_1 = 0.5$, $K_2 = 0.3$, $K_3 = 0.2$

Later in the article Gordon and Munson discussed statistically fitting S-curves to data, to demonstrate the typical S-shaped growth cycle of technology. Several versions of S-curves were discussed, but the one fitted to the computer example (by numerical methods) was of the form,

$$SOA = \frac{L}{2}\,[1 + \tanh A\,(t - t_o)]$$

where, L = the theoretical upper limit of the variable

A = a constant that depends on the slope at the inflection point

t = time of technology (as in Alexander and Nelson)

t_o = the time associated with the inflection point

The result valued K_1 at 0.14, K_2 at 0.38 and K_3 at 0.49.[17]

As an aside, Gordon and Munson did not discuss the reliability of their models. But they read the calculated value of the L parameter for the S-curve as an estimate that the ultimate limit to computing technology will be "an improvement of about 25 percent over the performance of the IBM 3033."[18] In fact, today's leading computers are about 100 times faster, are roughly comparable as to cost per computation, and contain about 60 times more storage capacity than the IBM 3033. Using the two

versions of Gordon and Munson's model for computers (two sets of K_is), the implication is that performance has in fact increased by from 4340 to 6200 percent over that of the IBM 3033 in less than a decade!

Another contribution made by Gordon and Munson was to suggest the use of factor analysis as a method for grouping proposed technology parameters into clusters that have similar behavior or influence on SOA.[19] A possible advantage of this procedure is that it might allow initial inclusion of many more parameters, but subsequent stages of the analysis could be based on a more limited set of clusters rather than on the many parameters who's information content had been so aggregated. The favorable result is parsimony. However, a disadvantage they see in factor analysis is some loss of intuitive appeal and increased, perhaps unnecessary, complications in modeling.

Knight, 1985. Knight examined 120 computer systems introduced between 1963 and 1979. His study made two important contributions: he distinguished sharply between functional and structural measures of technology, while developing a relationship between the two; and he examined the movement of a functional measure of computer technology over time.[20]

Knight defined the concept of functional measures of computer technology as, "The capability of each system to perform its intended tasks."[21] The measurements he selected to indicate how well computers perform their intended tasks were,

Computing power	in	Operations per second
The cost of the computing equipment	in	Seconds per dollar of equipment cost
Computing reliability	in	Mean number of operations between failures
Communications cost	in	Seconds per dollar of communications cost

The structural characteristics of a system are those describing the technical make-up of the machine itself. Knight provides a detailed description of a computer's structure which was based on specifications articulated earlier by Burke, Goldstine and von Neumann.[22] The designs are specified as follows:

Memory unit ==>
- Primary internal memory
- Secondary internal memory
- Dead storage

Arithmetic unit ==>
- Operations:
  - Arithmetic registers
  - Fixed point arithmetic
  - Branching
  - Instruction alteration
- Number system
- Arithmetic mode

Control unit ==>
- The instruction source
- Order of operations
- Communication to and from the computer
- Timing of operations
- Error check

Input-out unit ==>
- Primary input-output system
- Secondary input-output system
- Tertiary output system

Knight carefully pointed out that several computers with different structural characteristics can be functionally

equivalent, but that the reverse does not hold. That is, structure determines functionality, but functionality does not necessarily determine structure.[23]

Knight's objective was to determine the functional characteristics of a large sample of computers and to trace the advance of those characteristics through time. He began by stating that reliability and communications cost were too installation-specific to be determinable by computer, so his focus was limited to power and equipment cost (or, more accurately, computer equipment economy since the variable is calculated by dividing usable seconds of system operations by lease price).

Knight also stated that computing power is software-dependent to a significant degree. Therefore, he developed a model to convert computer structure, which is more directly measurable, into a measure of computing power. (Remember that structure determines functionality.)

As a final step, Knight determined the relationship between computer equipment economy and computing power through time (with both variables expressed in log form). His work can be summarized in the following display. (See Figure 1.3 on the next page.) The computers introduced to the market during the 1963-64 time period were modest in terms of economy, and can be characterized as low power. Computers from the 1979 era were considerably higher in power and more variable in their economy. Overall, there appears to be a roughly linear, negative

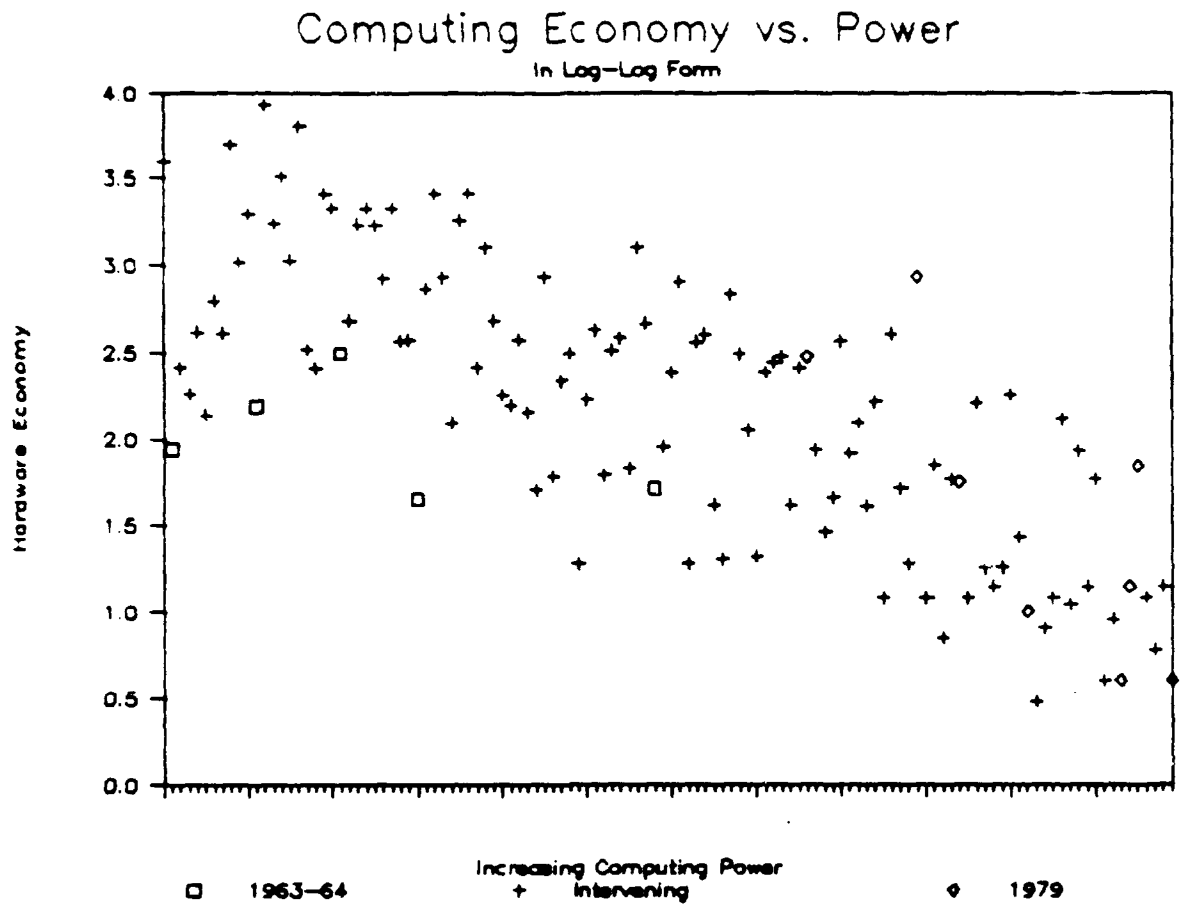

Figure 1.3 Summary of Knight's Work

relationship between the two. A word of caution is in order, however. While "seconds per dollar" is certainly an attribute of interest to users, the price a manufacturer charges may be less a function of the computer's technical prowess than of the firm's marketing strategy. Therefore, "cost"-based technology variables may show performance correlations due more to market forces than to an underlying SOA-based relationship.

In passing, Knight provided a test of Grosch's law. The test was applied over two sub-strata of the sample, and concluded that Grosch's law holds for the computer variables he studied;

that is, computing power increased roughly as a function of cost squared. Where Grosch's law would have predicted an "alpha parameter" of -0.5, Knight calculated an actual value of -0.656 for the 1963-71 time period and -0.668 for 1972-79.[24]

Martino, 1985. This paper by Joseph Martino extended Dodson's earlier work on ellipsoids by making an important change. Martino also tested the model on four data sets.[25] The alteration he made was to allow higher-order versions of the surface (where an ellipsoid is a second-order representation). His data sets encompassed clipper ships, jet engines, propeller-driven aircraft and power transistors.

Allowing higher-order versions of the surface required modification of the least squares fitting procedure used by Dodson. Rather than minimizing the mean square deviation, Martino had to minimize the mean absolute deviation. This required that the surface be fit by iterative experimentation and inspection rather than by the exact-fitting algorithm developed by Dodson.

Clipper ships were divided into two subsets by date built, 1820-1839 and 1840-1855. (The break concurred with the development of a design method which used iron bars to minimize a lengthy ship's susceptibility to a problem known as "hogging." This development allowed designs of considerably increased length, thereby increasing performance.) Three variables were used to describe technology, displacement, length-to-camber ratio and draft. The surface fit was of order six. Results were as

expected: the 1840-1855 group revealed use of a higher level of technology than did the 1820-1839 group.

Jet engines were compared using thrust, thrust-to-weight ratio and fuel economy. Second-order surfaces described turbofan engine technology of a first and second generation. The results were generally as expected, but there was intersection between the two surfaces due to one anomalous engine. A surface fit to turbofan versions of jet engines was higher than a surface for contemporary turbojets with no overlap between the groups.

Propeller-driven aircraft were compared using sixth-order surfaces fit to structural efficiency, maximum speed and useful load through four generations of aircraft. Surfaces could be fit to only three of the four generations, and there was one intersection, but results were generally good.

Power transistors were compared using four variables; power dissipation, speed of operation, maximum allowable voltage and the "percent safe operating area."[26] Surfaces (of unspecified degree) were fit to two groups, with a break occurring in the late 1970s. As Martino notes,

> The tradeoff surfaces intersect, which means that the newer technology will not completely displace the older. There are regions of the parameter space where the old technology is still superior to the new. . . . Nevertheless, each technology does in fact lie on a tradeoff surface which defines the combinations of parameters accessible to the designer.[27]

From the Martino piece we learn that the ellipsoid method, as adapted, works well with a wide range of technologies. It is also worth noting that the technologies examined encompass at least three different levels of system aggregation. The clipper ships and propeller-driven aircraft are whole systems; the jet engines are sub-systems; and the power transistors are relatively minor components.

Literature on Cost of Advancing SOA

A limited amount of research has been done on the cost of advancing states-of-the-art. To date, the work has not been definitive in terms of providing answers, but it does provide insight into the structure and difficulty of the questions.

Dodson, 1977. The focus of this paper by Dodson was cost estimation--both R&D cost and procurement cost.[28] The empirical data used was a group of general purpose avionics computers. Three indicators of technological capability were used,[29]

X_1 = number of distinct instruction types (add, shift, etc.)
X_2 = number of operations per second (10^3)
X_3 = density of the central processing unit (lbs/ft^3)

A multiple linear regression was run where the dependent variable was the year of development. This gave the following equation,

$$Y_e = 1961.3 + 0.03\ X_1 + 0.015\ X_2 + 0.06\ X_3$$

Y_e was calculated for each computer in the sample. Dodson reasoned that if $Y_{actual} < Y_e$ then that particular computer was developed "ahead of it's time"--that the SOA had been advanced by the development of that model. Conversely, if $Y_{actual} > Y_e$ then the computer was "behind the times". Therefore, $Y_e - Y_{actual}$ measured the SOA advance for each computer.

The next step was to associate SOA advance with R&D cost. This was done with another regression. The result was,

$$Y = 6.11 + 2.7\,X_1 - 4.57\,X_2 + 14.8\,X_3$$

Where,

Y = R&D cost (in 1974$\$10^6$)

X_1 = SOA advance, $Y_e - Y_{actual}$

X_2 = 1 for microprogrammable computers, 0 for synchronous computers

X_3 = 1 for space computers, 0 for airborne computers

Dodson reported that the empirical relationship fit to this equation was "not altogether satisfactory."[30] His explanation for the lack of fit was that there are other cost elements associated with R&D which were not identified or included in the study. Therefore, Dodson attributes the inadequacy of the model to a lack of data and attendant incomplete modeling.

Procurement cost was estimated from a cost estimating relationship (CER) which incorporated the year of technology as

an independent variable. According to Dodson, this is necessary to compensate for the fact that production technology changes through time. A more advanced design would be more costly to produce with older manufacturing technology. More advanced production technology would cause the procurement cost to drop.

Dodson developed the following regression equation from data on avionics digital processing units,[31]

$$\ln C = 8.41 - 0.11\, X_1 + 0.249\, X_2 + 0.217 \ln X_3 + 0.274 \ln X_4$$

where,

C = cumulative average cost at $Q = 100$ in 1974\$$10^3$

X_1 = year of development completion - 1900

X_2 = 0 if microprogrammable, 1 if hard-wired synchronous

X_3 = (10^3 operations per second)(word length, bits)

X_4 = number of distinct instructions

No fit statistics are reported for the regression, but there is a plot (shown in Figure 1.4 on the next page) which seems to indicate Dodson had better success with estimating procurement costs than R&D costs.

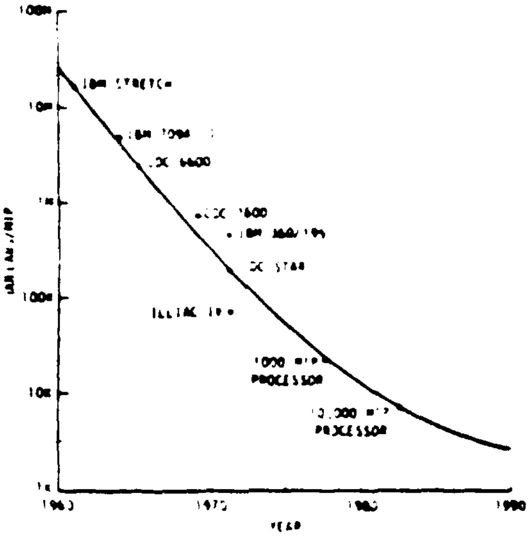

Figure 1.4 Dodson's Computer Production Cost Curve

Dodson, 1985. In this 1965 article Dodson reports much of the same material contained in his 1977 piece, but with some important additions.[32] Specifically, he introduced the possibility of using family trees, factor analysis, and technological distance scores.

The "family trees" concept simply structures the evolution of successive renditions of developing technology. For example, Dodson points out that,

> Individual rocket motors have "evolved" directly from some predecessor. . . . each successive model having one or more refinements or changes . . . . It then [becomes] a point of interest to develop measures of the change from model to model, our hypothesis being that the required development cost would be positively related to the amount of change.[33]

The simple but perhaps often overlooked implication is that R&D

cost researchers must have access to complete generations of technology if cost is to be properly related to amounts of change. A missing generational point could cause the amount of change effected by a certain expenditure to be overstated.

Factor analysis is a statistical method which, today, is more commonly used by researchers when investigating social science problems. Basically, it accumulates the statistical influence of several correlated variables to form "factors". The method frequently enables the researcher to reduce the information content of a large number of variables into a relatively small number of factors (or composite variables). Factor "scores", the calculated values of the composite variables, can then be used for further analysis. The method is of considerable advantage when sample sizes are limited because it enables subsequent analyses to be performed with more degrees of freedom. An analyst can also use axis "rotation" to identify associative relationships where none were apparent from the original data.[34]

Dodson developed nine variables describing rocket motor technology and evaluated these variables across a sample of 60 motors developed between 1950 and 1968. Then he ran a factor analysis and identified four factors which, collectively, explained 83.5% of the variance in the data.[35] However, the loadings were not particularly strong.

Next Dodson described "Technological Distance Scores".[36] A TDS is the Euclidian distance between two systems, where the

technology location of each system is measured in terms of _N_ variables.

$$d_{ij} = \sqrt{\sum_{k=1}^{N} (S_{ik} - S_{jk})^2}$$

where,

d_{ij} = Euclidian distance (or technological distance) between the _i_th and _j_th systems

S_{ik} = variable value of the _i_th system for the _k_th variable

S_{jk} = variable value of the _j_th system for the _k_th variable

N = number of variables

Dodson applied the TDS measurements to his sample of rocket motors using factor scores for variables. The only conclusion he was able to make was that "TDSs show promise of being a useful indicator of development cost and risk".[37]

Literature on Product Cost and Advancing SOA

Alexander and Mitchell, 1985. The Alexander and Mitchell paper addresses product cost as an SOA design objective. That is, product cost is viewed as one among many performance variables that describe the technical parameters of a product.[38]

The figure reproduced below is a summary of the concept.[39] Greater values of other performance variables can always be achieved, but at greater cost. To move from curve t_0 to the t_1

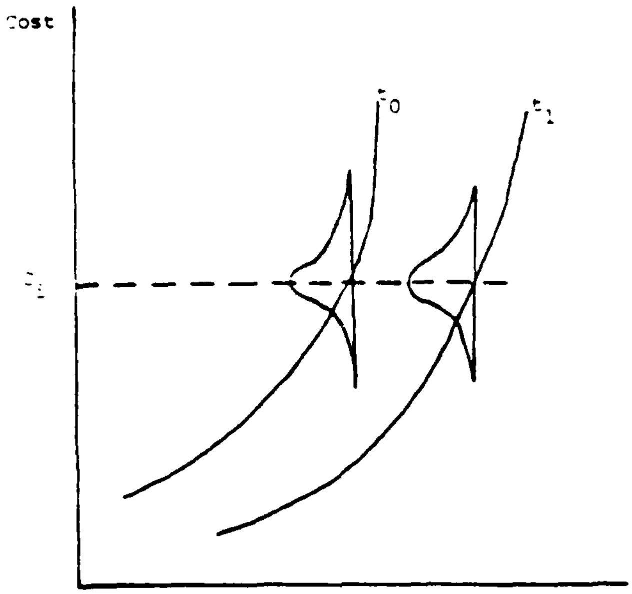

Figure 1.5 Summary of Alexander and Mitchell's Concept

curve (in any direction) represents an SOA advance. The vertical bell-shaped curves portray cost uncertainty for given levels of performance.

Alexander and Mitchell examined several sets of data including milling machines from the early 1860s through the 1970s, and commercial turbine-powered aircraft from 1958 through the early 1980s.[40] Their results show inflation-adjusted product costs rising over time after adjusting for level of product technology. The following is a result for the cost of airframes:[41]

$$\ln(\text{airframe cost}) = -9.13 + 0.91 \ln(\text{airframe weight}) + 0.0039\ \text{time}$$

$$R^2 = 0.93,\ SEE = 0.19,\ N = 24$$

where,

airframe cost = cost of aircraft minus engines, deflated by airframe cost index

airframe weight = weight of airframe (aircraft empty weight minus engine weight)

time = aircraft certification date; quarter years since 1942, third quarter.

However, it is crucial to note that the "cost" referred to here is the purchase price of the unit of equipment itself. The total cost of <u>using</u> the unit for its intended purpose is an entirely different matter. (The two concepts are analogous to the DoD notions of procurement cost versus life-cycle cost.) Alexander and Mitchell point out that,[42]

> Productivity estimates based on product characteristics may not adequately reflect the total value of the product to users, partly because of the noninclusion of all the relevant characteristics. For example, seat-mile costs are a function of the number of seats, operating costs, fuel costs, and speed as well as of aircraft price.

The graph below (See Figure 1.6 on the next page.) clearly indicates that the cost per seat-mile for commercial aircraft has dropped significantly over the last twenty years. Even if other performance characteristics had remained constant this would represent a significant technology advance in terms of utility to the user.

The most important concept to emerge from the Alexander and Mitchell work is that product cost should not necessarily be a design variable; the more appropriate measure of economy is life-

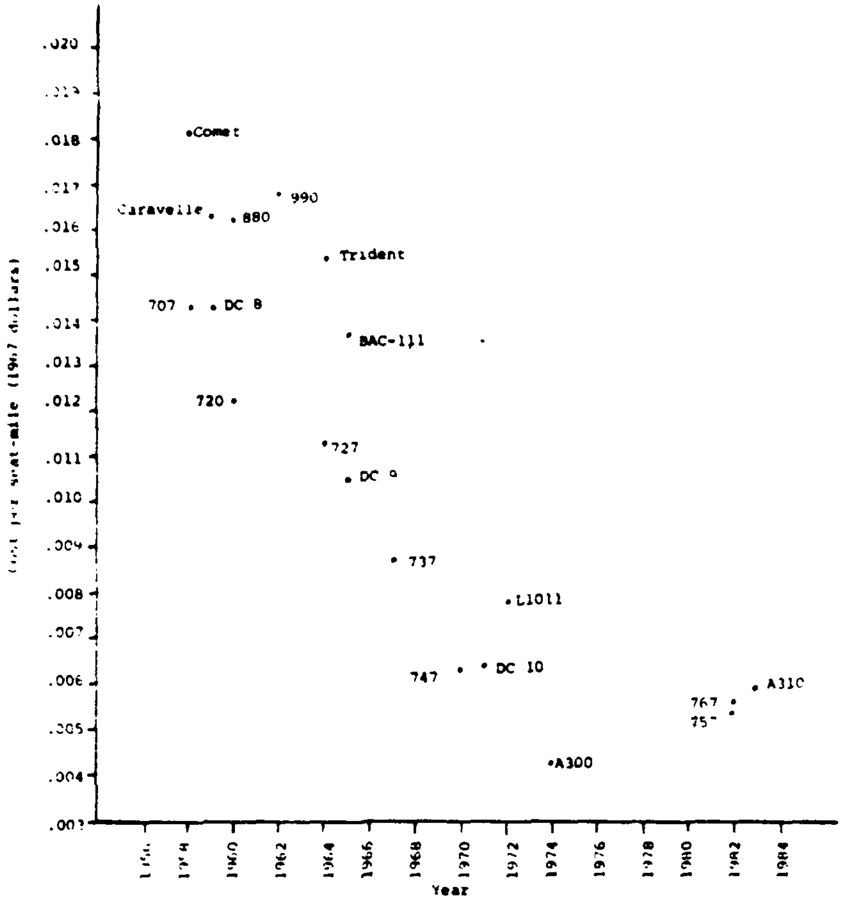

Figure 1.6 Alexander and Mitchell Seat-Mile Cost Plot

cycle cost. But even then, there are other factors which may override cost.[43]

> Noise, safety, pollution, comfort, convenience, flexibility, range, reliability, and countless other attributes are routinely considered by aircraft buyers and their customers.

Miscellaneous Literature on SOA

Hovanessian, 1975. Hovanessian discussed, in general terms and without the benefit of empiricism, many aspects of research

and development management.[44] Among the topics treated were,

> Methodology for integrated-system R and D, system design concepts, major system components, matrix organization, cost effectiveness, life-cycle cost, and customer-acceptance requirements.[45]

Two of the more useful concepts Hovanessian identified were an expanded set of user-oriented product characteristics and a comprehensive illustration of life-cycle cost.

Hovanessian, like Alexander and Mitchell, points out that user utility of a technological system is only partially described by using scientific variables alone. Equally important in his mind are "customer acceptance" parameters "which include such factors as maintainability, availability, degree of automation, operator approval, and improvements over previous systems."[46]

Hovanessian's representation of life-cycle cost includes three phases; RDT&E, investment and operating. He describes these phases in terms of rates of spending as a function of time. Each phase can therefore be represented as a spending pattern.

While Hovanessian's spending patterns are not empirically based, it is easy to see that empiricism could be useful to the proposal evaluation process in at least two ways. First, the present value of the cost of alternate technologies could be compared with each other and with other, more technical, descriptions of the proposals. Second, budgeted to-date and actual to-date spending could be compared for control purposes.

Lienhard, 1979. This paper studies the rate at which technology is improved, and how (whether) this rate has changed through time.[47] The basic metric Lienhard uses is the order of increase, or "*n*-folding", that has taken place during a working "lifetime", which he defines as 30 years. The formulation he uses is,[48]

$$\frac{Q}{Q_0} = n^{(t - t_0)/30} = e^{(t - t_0)[(\ln n)/30]}$$

where,

Q = the value of the attribute to be improved measured at time t

Q_0 = the initial value of the attribute quantity, measured at time t_0

Lienhard points out that an alternate way to look at this formula is to think of $30/\ln(n)$ as the "time constant," T--the time required to complete one e-folding of Q.

It should be noted that Lienhard's work is based on single-variable measurements. In other words, only one attribute of the technology in question is tracked through time.

Several forms of technology were studied. The results can be summarized in a single table:[49]

Technology	Attribute	Dates	*n*
Mechanical clock	Accuracy	1400-1920	1.95
Steam power	Thermal efficiency	1742-1850	2.5
Land transport	Speed	1803-1965	1.86
Low temperatures	Difference in temper	1860-1936	21.5
Air transport	Speed	1884-1967	10.1

Lienhard makes several observations based on his analysis. First, he states that technology advance sometimes depends on motivation. For example, regarding air transport speeds he states that,[50]

> It seems unlikely that there remains much motivation to continue increasing air speeds. They have now reached such enormous values that problems of starting, stopping, and turning determine how fast a person can be taken from one place to another.

Another interesting observation is that one technology must sometimes "wait" on another. For example, Rozier experimented with balloon flight, reaching a maximum height of about 9,000 feet in 1783. Then little progress was made for about a century and a half while aviation awaited the development of high-altitude breathing equipment. Finally, rapid advance was again made from 1923 until 1957, "when orbital vehicles constituted a replacement technology."[51]

Lienhard also observed that the rate of change in technological growth increased dramatically in the middle of the 19th century. Other authors have observed this as well. Lienhard's explanation is that, "Suddenly, technology began to breed more technology."[52]

His final observation is potentially the most useful. He says,

> [An] empirical fact which we have heretofore taken for granted, but which the data show to be unwaveringly

true, is that the rate of improvement of a particular technology, once established, does not change.[53]

If this is literally correct (and his data do tend to support the observation), there are some major implications for the cost, and even the feasibility, of undertaking advances in SOA. Specifically, the anticipated advance could be expected to occur only by some quasi-naturally established date. Attempts to accelerate this natural process would undoubtedly be very costly. It would follow that those who express technology levels as simply a "date", or as a "year of technology", have good reason for doing so!

Foster, 1986. Technology advancement forecasting is really the controlling theme of this 1986 paper by Foster.[54] He opened with a familiar but important discussion on the identification of performance parameters. He pointed out that, "The performance parameters . . . must be related to key design factors", and that, "The best approach is to pick a few areas that are critical and concentrate on them." He also added that it is "important to recognize that the performance parameters will change over time."[55]

Foster's discussion then turned to forecasting the future of technology by fitting S-curves and determining limits. He does not offer very specific solutions, but he does articulate the possibilities of physical limits, and he identifies questions that relate to mechanisms that might limit the performance of the relevant technology: "Will it be thermodynamics? Strength of

materials? Chemistry? Laws of motion? Some fundamental physical force?"[56]

Foster then turned to S-curve fitting. Here he pointed out the importance of historical analysis and suggested the use of "logistics" or "Gompertz" curves. Finally, he warned against over-simplicity:

> The simplest approach is to make the top part of the curve symmetrical with the bottom part and draw a straight line connecting the points. This approach is fast and cheap. It also produces the least insight.

One very valuable insight Foster provided was to synthesize earlier work by Putnam on the relationships between development cost and development time.[57] Foster's formulation was,[58]

$$\text{Project cost} = \text{Projected performance}^{a}/[\text{Efficiency} \times \text{Time}^{b}]$$

where <u>a</u> and <u>b</u> are parameters. Foster suggests the parameters may be specific to individual contractors. Note that (if <u>b</u> is positive) a <u>reduction</u> of the time available for the undertaking tends to increase project cost.

<u>Becker and Speltz, 1986</u>. This paper reports another effort to plot S-curves and, in particular, to forecast the "turning point", or the point at which the advance of the subject technology will cease.[59] The specific technology studied was a class of insecticides known as pyrethroids. "The question facing the R&D management was whether or not research in the pyrethroids should be continued."[60]

The procedure was reported only in broad-brush terms, and apparently was accomplished principally from visual inspection of historical plots. The illustration below summarizes background work on organophosphate insecticides.[61]

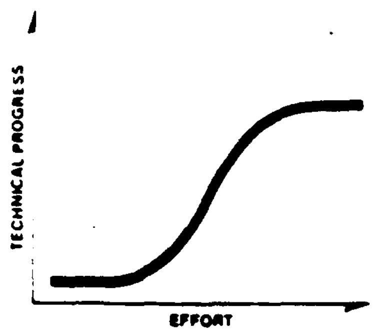

Figure 1 —The S-curve of Technical Progress Versus Effort.

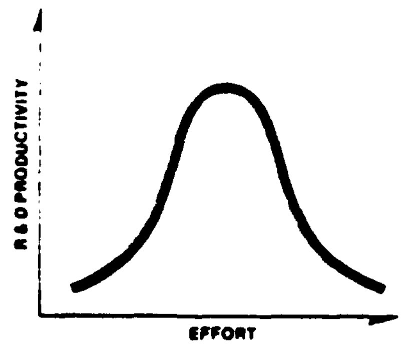

Figure 2.—The R&D Productivity Curve.

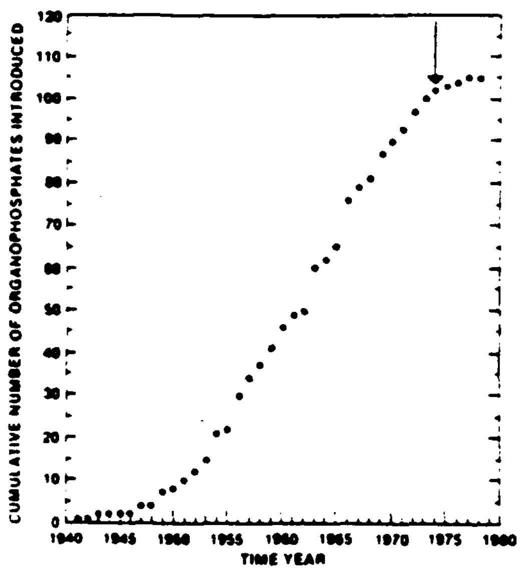

Figure 3.—The S-Curve for Organophosphate Insecticides.

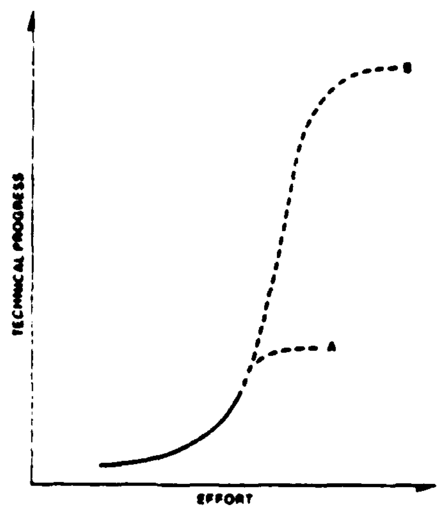

Figure 4.—Predicting the Shape of the S-Curve.

Figure 1.7 R & D Progress and Productivity vs. Effort

The curve in Becker and Speltz' Figure 1 shows the theoretical advance of technology, while Figure 2 demonstrates marginal payoff for incremental research effort (productivity). Becker and Speltz suggest that research efforts should be abandoned once marginal payoff passes the peak, or just past the inflection point in Figure 1. (This is a premise with which economic theorists would disagree. The more generally recommended position would be that effort should continue so long as marginal benefits exceed marginal costs.)

Figure 3 above is an attempt to plot an S-curve for organophosphate insecticides. The plot implies that the underlying technology had matured by about 1974 or 1975. However, it is worth noting that an analyst positioned in, say, 1955 or in 1962 might easily have drawn the incorrect conclusion that the curve had peaked. Ex ante estimates of the technological limits are at best difficult to make. The projection labeled "A" in Figure 4 illustrates the magnitude of error that might easily be committed.

Becker and Speltz completed their analysis by examining the state of development of five "distinguishable attributes". The attributes were.

- Spectrum of activity
- Increased soil activity
- Systemic activity
- Reduced fish toxicity
- Reduced cost

Their conclusion was "that improvements which would represent a technological advance for the pyrethroids were not likely."

CONCLUDING COMMENTS

This chapter began by pointing out that the cost of developing SOA extensions relates to the scale of the undertaking. Then the more important literature in the field was surveyed in order to examine the techniques currently available for costing development contracts. In this concluding section the objective will be to step back and examine SOA costing trends and the challenges that lie ahead.

SOA Measurement

The art of measuring SOA extensions was first approached with rigor by Dodson and Graver, who reported an important theoretical advance in 1969.[62] The innovation represented by their work was the use of (convex) ellipsoidal hypersurfaces to portray stages of SOA. The level of SOA advance incorporated in a system was represented by the radial distance of a desired point from the most current ellipsoid.

In order to make use of the Dodson and Graver approach technological parameters must be specified in such a way as to collectively describe the overall level of technology embodied in the systems or subsystems studied. Dodson and Graver took care

to point out that if the technique was to be useful, the parameters used "should be among those that are typically ascertainable during the early decision-making stages of the system life-cycle."[63]

Alexander and Nelson's 1972 RAND report articulated an important limitation of the Dodson and Graver approach--that is, the progression of technology must conform to an assumption of "continuity".[64] In effect, this limitation qualifies parametric SOA measurement models for use only when measuring evolutions in technology.

Alexander and Nelson, like Dodson in 1977,[65] analyzed empirical data to test SOA measurement theory, but both they and Dodson were able to use only linear methods, not ellipsoids, with any degree of success. Their model used the "date of technology" as the dependent variable. A 45° line thus defined an expected date of technology over the period.

Others have tried second-order versions of SOA equations, and even multiplicative models. The 1981 work of Gordon and Munson is an example. They added insight, but at the empirical testing stage of their analysis they had to resort to subjective methods to establish weights for parameter influence.[66]

Martino extended Dodson's work by allowing higher-order equations, but he was forced to use iterative experimentation and inspection as a fitting method.[67] On the other hand, Knight used Grosch's law and empiricism to argue for the fundamental correctness of second-order relationships. Grosch's law, "would

have predicted an "alpha parameter" of -0.5;" Knight calculated an actual value of -0.656 for the 1963-71 time period and -0.668 for 1972-79.[68]

SOA Extension Costing

There have been almost no really successful studies relating development cost with SOA extension. Perhaps the only one of any significance was published by Dodson in 1977.

Dodson attempted to establish a relationship between degrees of SOA extension and development cost by first running a linear regression in which various technology parameters were the independent variables and the dependent variable was the year of development.[69] Residuals from this regression then became an independent variable which was regressed against development cost. Dodson reported that the fit of this equation was "not altogether satisfactory."[70]

Suggestions for Future Improvements

This literature review suggests several ways in which our ability to measure and cost SOA extensions may be improved. First, more accurate SOA measurements should be developed. This effort will call for empirically based parametric models with somewhat more detailed input.

Gordon and Munson (1981) were the first to suggest the use

of factor analysis as a method for grouping proposed technology parameters into clusters that have similar behavior and influence on SOA.[71] The advantage of this method is that the effects of many variables can be condensed into a manageable number. But the method has not been tested in terms of its promise for improving cost estimation accuracy.

The technologies that have been examined in the SOA measurement work encompass at least three different levels of system aggregation--all relatively successfully. This implies that appropriate data bases might be enlarged by examining technologies at the subsystem level when one subsystem is used in more than one system.

A additional untested suggestion is that "technological distance scores" (determined from ellipsoids) might be a useful measure of SOA extensions.[72] However, Dodson's attempt to use them was unproductive; the only conclusion he was able to make was that use of technological distance score measures "shows promise".

Lienhard's 1979 study of the rate at which technology is improved provided a provocative suggestion that needs consideration.[73] He suggested there is an essentially _fixed_ rate at which any given technology _can_ be improved.

> [An] empirical fact which we have heretofore taken for granted, but which the data show to be unwaveringly true, is that the rate of improvement of a particular technology, once established, does not change.[74]

If indeed this is true, there are major implications for the cost, and even the feasibility, of attempting to undertake advances in SOA in a more compressed time frame.

Alexander and Mitchell argue that product cost should not necessarily be a design variable; a more appropriate measure of economy is life-cycle cost.[75] Hovanessian's representation of life-cycle cost includes three phases; RDT&E, investment and operating.[76] No methods for incorporating life-cycle cost have yet been developed.

Cost elements associated with R&D which have not been identified or included in a study can lead to incomplete modeling. The challenge is to more completely identify cost variables. Dodson argues that R&D cost researchers must have access to complete generations of technology.[77] Otherwise, the continuity, and value, of a data base is severely weakened.

Finally, the "S" shape of the SOA progression curve has also been examined. Foster's discussion addressed forecasting the future of technology by fitting S-curves and determining limits.[78] But the Becker and Speltz piece showed the great magnitude of the error that might be committed given the present state of knowledge--particularly when turning points are forecasted ex ante.[79]

ENDNOTES

1. Dodson, E. N., and C. A. Graver, "An Approach to Quantitative Measurement of Advances in State of the Art," Internal Memorandum (Releasable) IMR-997, General Research Corporation (Santa Barbara, 1969), 39 pgs.

2. Ibid., p. 4.

3. Ibid., p. 13.

4. Ibid.

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6. Dodson, E. N., "A General Approach to Measurement of the State of the Art and Technological Advance," Technological Forecasting, 1 (1970), pp. 391-408.

7. Ibid., p. 396.

8. Ibid., p. 406.

9. Alexander, A. J., and J. R. Nelson, "Measuring Technological Change: Aircraft Turbine Engines," Report No. R-1017-ARPA/PR, The RAND Corporation (Santa Monica, June, 1972), 37 pgs. See pp. 3-4. Also in Technological Forecasting and Social Change, 5 (1973), pp. 189-203.

10. Ibid., p. 21.

11. Ibid., p. 25.

12. Ibid.

13. Ibid., p. 32.

14. Gordon, T. J., and T. R. Munson, "A Proposed Convention for Measuring the State of the Art of Products or Processes," Technological Forecasting and Social Change, 20 (1981), pp. 1-26. The two models are described on pp. 3-6.

15. Ibid., pp. 8-16.

16. Ibid., pp. 16-18.

17. Ibid., pp. 18-24.

18. Ibid., p. 24.

19. *Ibid*., p. 8.

20. Knight, K. E., "A Functional and Structural Measurement of Technology," *Technological Forecasting and Social Change*, 27, (1985), pp. 107-127.

21. *Ibid*., p. 107.

22. Burke, A., H. H. Goldstine, and J. von Neumann, *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument*, Princeton, (1946), (2nd ed., 1947).

23. *Op. cit*., p. 109.

24. *Ibid*., p. 121.

25. Martino, J. P., "Measurement of Technology Using Tradeoff Surfaces," *Technological Forecasting and Social Change*, 27, (1985), pp. 147-160.

26. The explanation of this last measure would require more effort than the average reader would care to invest. Those who are interested might wish to consult *Ibid*., p. 158.

27. *Ibid*.

28. Dodson, E. N., "Technological Change and Cost Analysis of High-Technology Systems," *IEEE Transactions on Engineering Management*, (May 1977), pp. 38-45.

29. *Ibid*., p. 40.

30. *Ibid*. p. 41.

31. *Ibid*., p. 44.

32. Dodson, E. N., "Measurement of State of the Art and Technological Advance," *Technological Forecasting and Social Change*, 27, (1985), pp. 129-146.

33. *Ibid*., p. 140.

34. For a comprehensive treatment of factor analysis see Harman, H. H., *Modern Factor Analysis*, 3rd ed. (Chicago: University of Chicago, 1976).

35. See *Op. cit*., pp. 141-142. Those familiar with factor analysis might argue that, in fact, Dodson has explained only 75.7% of the variance. The difference is accounted for by the fourth factor which has an eigenvalue of only 0.701. Most analysts omit factors with eigenvalues less than one.

36. Ibid., p. 142.

37. Ibid., p. 143.

38. Alexander, A. J. and B. M. Mitchell, "Measuring Technological Change of Heterogeneous Products," Technological Forecasting and Social Change, 27, (1985), pp. 161-195.

39. Ibid., p. 176.

40. They also cite the work of others on automobiles and computers.

41. Op. cit., p. 184.

42. Ibid., p. 187.

43. Ibid., p. 194.

44. Hovanessian, S. A., "Research and Development of a Large-Scale Electronic System," IEEE Transactions on Engineering Management, Vol. EM-22, No. 3, (August 1975), pp. 94-101.

45. Ibid., p. 94.

46. Ibid.

47. Lienhard, J. H., "The Rate of Technological Improvement before and after the 1830s," Technology and Culture, (July 1979), pp. 515-530.

48. Ibid., p. 516.

49. Based on Ibid., Table 5, p. 526.

50. Ibid., p. 522.

51. Ibid., p. 524.

52. Ibid., p. 528.

53. Ibid., p. 529.

54. Foster, R. N., "Assessing Technological Threats," Research Management, (July-August 1986), pp. 17-20.

55. Ibid., p. 17.

56. Ibid., p. 18.

57. Putnam has done a great deal of work on development time and cost, but it has all been in a computer software development context. Nonetheless, many of Putnam's concepts are useful in the more general context of development activity. A good reference source is Putnam, L. H., Software Cost Estimating and Life-Cycle Control: Getting the Software Numbers, Computer Society Press, IEEE Computer Society (New York, 1980), 349 pgs. See particularly Chapter 10 and the series of three articles by Putnam and A. Fitzsimmons.

58. Op. cit., p. 19.

59. Becker, R. H., and L. M. Speltz, "Making More Explicit Forecasts," Research Management, (July-August 1986), pp. 21-23.

60. Ibid., p. 21.

61. Ibid., p. 23.

62. Op. Cit., 1969.

63. Ibid., p. 14.

64. Op. Cit., 1972.

65. Op. cit., 1977.

66. Gordon and Munson, op. cit., 1981.

67. Martino, Op. Cit., 1985.

68. Ibid., p. 121.

69. More accurately, the year of implementation. See Dodson, op. cit., 1977.

70. Ibid. p. 41.

71. Ibid., p. 8.

72. See Dodson, op. cit., p. 142.

73. Op. cit.

74. Ibid., p. 529.

75. Op. cit., 1985.

76. Op. cit., 1975.

77. Op. cit., 1985.

78. _Op. cit._, 1986.

79. _Op. cit._, 1986.

Chapter 2

MEASURING TECHNOLOGY

INTRODUCTION

The objective of this chapter is to formulate a measure of overall technology that is demonstrably applicable to the systems studied, and that will serve as satisfactory input for the next step, the cost estimation process, to be examined in Chapter 3. The working assumptions used in this chapter are:

1. The ellipsoid method developed by Dodson and Graver is theoretically correct in its second-order form.[1]

2. Factor analysis is an appropriate methodology for capturing the influence of a relatively large number of technological parameters.[2]

3. Any data set characterized by "technological continuity" can be used for empirical demonstration of the methodology to be developed.[3]

DATA SET

Obtaining reliable data in sufficient quantity to allow rigorous inquiry is a constant problem for cost analysts. Dodson has pointedly illustrated the usual scope of this problem in Figure 2.1 below.[4]

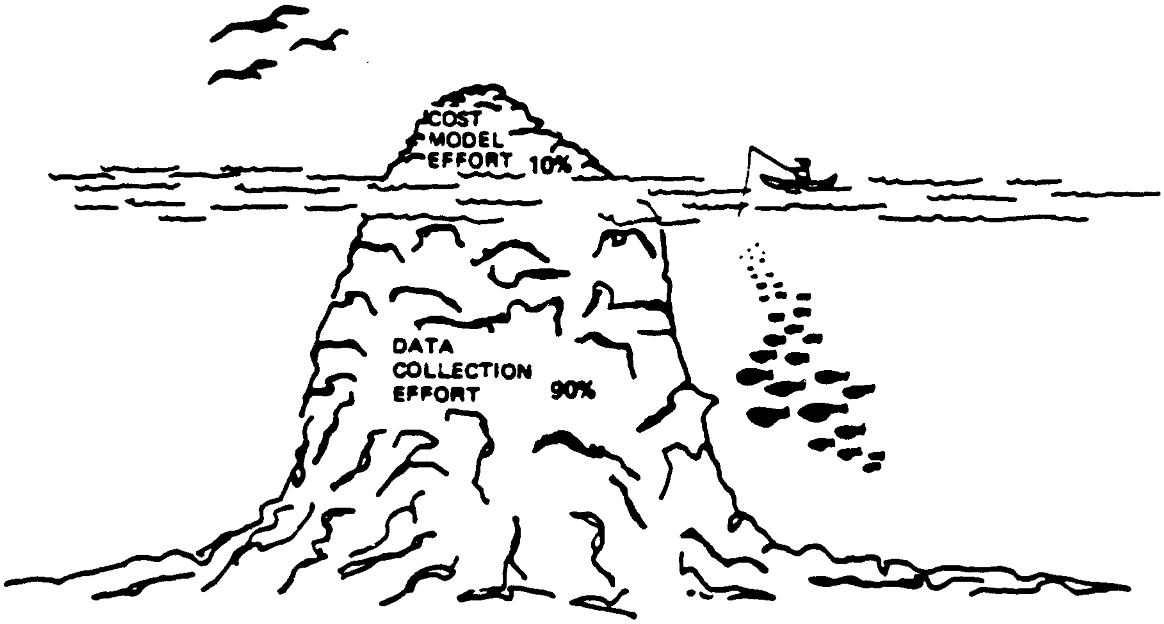


Figure 2.1 Dodson's View of Data Collection

Data describing various technological and cost parameters for 18 satellite programs were supplied by the United States Air Force.[5] The satellites described included several types, communications, surveillance, navigation, etc.; they were first launched between 1966 and 1986.

Variable Selection

The first step was to select variables that describe the technology embedded in satellites. Data describing 85 technical characteristics of each of the 18 satellites were available. The 85 properties are listed on the next page.[6]

SATELLITE DATA

ACS: SLEW RATE
ACS: ORIENTATION
ACS: POINTING ACCURACY
ACS: JIT REQ
ACS: JIT AMP
ACS: JIT FREQ
ACS: PROPELLANT WT
ACS: TOT IMPULSE
ACS: RCS FUNCTION
ACS: PRIM STAB METHOD
ACS: TORQ METH-COLD GAS
ACS: TORQ METH-MONOP
ACS: TORQ METH-BIPROP
ACS: TORQ METH-MAGN
ACS: TORQ METH-WHEELS
ACS: TORQ METH-CMG
ACS: MOM MGMT-COLD GAS
ACS: MOM MGMT-MONOP
ACS: MOM MGMT-BIPROP
ACS: MOM MGMT-MAG
ACS: MOM MGMT-SOLAR
ACS: MANEUVERABILITY
ACS: STATIONKEEPING
ACS: PER/PHASE CONTROL

LAUNCH METHOD
ORBITAL APOGEE
ORBITAL INCLINATION
DESIGN LIFE
POINTING ACCURACY
NUCLEAR HARDENING
NUMBER OF APPENDAGES
QUALITY: %CLASS B
QUALITY: %CLASS S

STRUC: %DEPLOYED WT
STRUC: MAT-ALUMIN
STRUC: MAT-MAGNES
STRUC: MAT-SIMP ALLOYS
STRUC: MAT-FIBERGLASS
STRUC: MAT-TITANIUM
STRUC: MAT-HONEYCOMB
STRUC: MAT-BERYLLIUM
STUCT: MAT-BORON/GRAPH
STRUC: MAT-HYBRID/MET MAT
STRUC: TYPE CONSTRUCTION

COMM: NO. CHANNELS
COMM: NO. TRANSMITTERS
COMM: NO. RECEIVERS
COMM: ANIT-JAM CAPABILITY
COMM: POWER REQ(W)

AKM: THRUST VECT CONT
AKM: DELTA V
AKM: NOZZLE MATERIAL
AKM: CASE COMP
AKM: DRY WEIGHT
AKM: PROP WEIGHT
AKM: SPEC IMPULSE
AKM: BURN TIME
AKM: TOTAL IMPULSE
AKM: PAYLOAD WEIGHT

EPS: ARRAY TOPOLOGY
EPS: STORAGE TYPE
EPS: BOL POWER (W)
EPS: ARRAY AREA(SQ FT)
EPS: TOTAL NO. CELLS
EPS: CELL EFFICIENCY
EPS: BAT CAP (AMP-HRS)
EPS: NO. BATTERIES
EPS: CELLS PER BATTERY

THERM: PASS-COATINGS
THERM: PASS-SLI
THERM: PASS-MLI
THERM: PASS CONDUCTION
THERM: PASS-CCHP
THERM: ACT-VCHP
THERM: ACT-1 PH FL LOOP
THERM: ACT-CAPPIL FL LP
THERM: ACT-2 PH FL LOOP
THERM: HEAT REJ TYPE
THERM: RADIATOR ORIENT
THERM: MAX TEMP(C)
THERM: MIN TEMP(C)
THERM: DUTY CYCLE(%)
THERM: DES COMPUTER HRS

TTC: NO. CHANNELS
TTC: NO. TRANSMITTERS
TTC: NO. RECEIVERS
TTC: ANTI-JAM CAP
TTC: TAPE R-BIT CAP
TTC: TAPE R-RATE(KBPS)
TTC: TAPE R-REC TIME(MIN)
TTC: POWER REQ(W)
TTC: TAPE R-QUANTITY
TTC: TAPE R-POWER REQ(W)
TTC: AUTON OPS(DAYS)
TTC: NO. COMMANDS

Figure 2.2 85 Properties Describing Satellite Technology

Some of the 85 properties included in the data set can be considered design objectives, but many others are simply byproducts of the design, or are not stated in a form that really says a great deal about the technology embodied. Therefore, technical expertise was essential in identifying and, in some

cases reconstructing, relevant variables.

Extensive data review, conversations and conferences took place among a group of satellite experts at the Naval Postgraduate School:

Dr. Allen E. Fuhs, Code 72

Distinguished Professor of Aeronautics & Space

Dr. Richard W. Adler, Code 62Ab

Adjunct Professor, Elec. & Comp. Engineering

Mr. Marty Mosier, Code 72

Staff Engineer, Space Systems

This effort led first to the construction of several composite variables based on the guideline recommendations originally suggested by Dodson and Graver in 1969:

First,

> The selection of SOA-determining characteristics should be concentrated on those that are at least partially influenced by engineering development decisions. The individual characteristics . . . represent constraints upon the achievement of other design characteristics which are--to a degree--goals of design.[7]

Second,

> . . . Characteristics should be specified so that increasing values of the characteristics correspond to greater technical difficulty.[8]

Finally,

> . . . The characteristics should be among those that are typically ascertainable during the early decision-making stages of the system life-cycle.[9]

The last of these guidelines is particularly important if the final analytical output is to be useful for early feasibility study, or when development funding is being sought, or when attendant budget decisions are being made.

The result of the conferences was consensus identification of 18 variables or composite variables that can be used to describe satellite technology:

Attitude Control System (ACS) variables:

ACS1 -- Reciprocal of Pointing accuracy.

ACS2 -- Primary stabilization method -- coded;
spin = 0, moment, inertial, dual = 1.

ACS3 -- Maneuverability, yes-no -- coded;
no = 0, yes = 1.

Apogee Kick Motor (AKM) variables:

AKM1 -- Specific impulse.

AKM2 -- Propellent weight / Dry weight.

Communications variable:

COMM -- Power required.

Electrical power systems variables:

EPS1 -- Battery Capacity.

EPS2 -- Beginning of life power / Array Area, compensated for stabilization & array deployment.

EPS3 -- Array topology -- coded;

Body = 0, Fixed = 1, Movable = 2

Mission or environmental variables:

LIFE -- Design life.

NHARD -- Nuclear hardening -- coded;

Geo = Leo = 4, Elliptical = 7, War = 10

LAUNCH -- Launch method -- coded;

ELV = 0, Shuttle, Dual = 1

QUALS -- Quality percent class S

APOGEE -- Orbital apogee * Design life * (% Quality S + 0.8 % Quality B) / 10000

DESIGN -- Design life / (% Quality S + .1 % Quality B).

Structure variable:

STRUC -- Percent deployed weight.

Thermal variable:

THERM -- Max temperature - Min temperature.

Tracking telemetry control variable:

TTC -- Autonomous operating days.

These 18 variables were determinable for each of 18 satellites, with one exception; THERM was missing for Satellite R.[10] The variables and their values are listed on the next page.

SYSTEM LEVEL DATA

VARIABLE	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
	SATELLITE																	
ACS1: RECIP(POINTING ACCURACY)	4.00	10.00	12.50	2.00	1.00	1.00	0.20	2.56	6.67	0.50	3.85	0.50	10.00	0.20	2.86	2.00	3.33	5.00
ACS2: PRIM STAB METHOD S=0 M,T,D=1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	1	1	0	1
ACS3: MANEUVERABILITY N=0 Y=1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	1	1	1
AEM1: SPEC IMPULSE	285.50	0.00	0.00	287.15	0.00	282.90	0.00	0.00	0.00	0.00	291.00	0.00	0.00	290.00	289.60	284.00	291.00	286.70
AEM2: PROP WEIGHT/DRY WEIGHT	14.20	0.00	0.00	11.23	0.00	9.38	0.00	0.00	0.00	0.00	12.03	0.00	0.00	8.89	10.78	9.22	9.59	13.11
COMM: POWER REQ(W)	800.00	0.00	480.60	360.50	0.00	5.60	20.00	400.00	920.70	0.00	0.00	0.00	470.00	0.00	298.00	235.00	217.00	768.46
EPS1: BAT CAP (AMP-HRS)	102.00	30.00	96.00	45.00	60.00	12.00	0.00	20.00	120.00	502.00	18.00	18.00	30.00	10.00	20.00	20.00	60.00	68.00
EPS2: (BOL POWER(W)/ ARRAY AREA(SQ FT))*P1*N WHERE N= 0 IF NOVAD .5 IF FIXED & INERTI .5 IF BODY & MOMENT 1 IF FIXED & DUAL OR SPIN 1 IF BODY & DUAL OR SPIN	9.30	9.00	8.73	9.56	7.32	9.24	6.28	9.65	7.81	28.90	41.67	7.07	6.15	60.50	50.78	10.79	10.56	8.45
EPS3: ARRAY TOPOLOGY B=0 F=1 M=2	3	2	2	2	1	0	0	0	2	1	1	0	1	0	0	0	0	2
LIFE: DESIGN LIFE	60	30	120	60	12	36	36	60	120	12	12	12	24	6	84	60	84	84
NHARD: NUCLEAR HARDENING G,L=4 E=7 N=10	10	4	10	7	4	7	4	4	4	4	4	7	4	7	4	4	4	4
LAUNCH: LAUNCH METHOD ELV=0 S,B=1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
QUALS: QUALITY % CLASS S	100	0	50	100	0	0	0	0	50	0	0	0	100	0	0	0	100	0
APOGEE: ORBITAL APOGEE * DESIGN LIFE * (%QUALITYS + .6%QUALITYB)/50000	11400.00	100.00	20868.84	6300.00	19.97	6624.00	5241.60	9264.00	20844.00	28.80	30.72	211.20	4617.52	120.00	12969.60	9216.00	16227.96	12902.40
DESIGN: DESIGN LIFE/(%QUALITYS + .1%QUALITY B)	0.60	3.00	2.18	0.60	1.20	3.60	3.60	6.00	2.18	1.20	1.20	1.20	0.24	0.60	8.40	6.00	0.84	8.40
STRUC: % DEPLOYED WT	17.00	12.00	5.00	8.00	4.00	2.00	0.00	6.20	15.00	28.00	0.00	0.00	12.60	0.02	0.00	0.00	0.00	10.00
THERM: MAX TEMP - MIN TEMP	33.30	10.00	63.00	25.00	16.70	34.00	51.00	16.70	32.00	25.00	50.00	15.00	30.00	36.00	7.80	26.10	26.10	
TTC AUTON OPS(DAYS)	1.00	1.00	90.00	0.50	7.00	0.00	0.00	7.00	1.00	0.00	0.00	2.00	2.00	0.00	1.00	1.00	30.00	1.00

Figure 2.3 18 Variable Values for Each Satellite

FACTOR ANALYSIS

The values of all 18 variables for all 18 satellites were loaded into an SPSS^x (Release 2.1) data file. A factor analysis was run, asking first for the correlation matrix and 1-tailed significance levels. (The output is shown on pages 53 and 54.) The data are quite robust with high coefficients of variation and many significant correlations.

Since there are too many variables (18), the matrix was ill-conditioned. Some variables had to be eliminated from the analysis. Accordingly, variables were given an additional screening. Rejection would have been based first on <u>no</u> correlations with .05 or better significance. However, no variables could be eliminated on this basis.

STRUC was eliminated because the engineers felt some of data were incorrect. However, the remaining 17 variables were all candidates for further consideration.

The variables were next subjected to a principal components factor analysis using the varimax procedure for orthogonal rotation. Variables with large (greater than 0.50) negative loadings were eliminated based on Dodson's second guideline. This eliminated DESIGN, ACS3 and EPS2. QUALS was discarded next, because it had no substantial factor loading (no loading equal to or greater than 0.50).[11] The remaining 13 variables were factored again and clustered very nicely onto four factors with 78.5% of the variance explained.

ANALYSIS NUMBER 1 PAIRWISE DELETION OF CASES WITH MISSING VALUES

	MEAN	STD DEV	CASES	LABEL
ACS1	3.78722	3.71633	18	RECIP(POINTING ACCURACY)
ACS2	.77778	.42779	18	PRIM STAB METHOD--S=0, M.I.D=1
ACS3	.83333	.38348	18	MANEUVERABILITY--N=0, Y=1
AKM1	143.76944	147.95211	18	SPEC IMPULSE
AKM2	5.46833	5.77163	18	PROP WEIGHT/DRY WEIGHT
COMM	275.32444	318.02799	18	POWER REQ(W)
EPS1	68.38889	113.65021	18	BAT CAP (AMP-HRS)
EPS2	15.64556	14.19114	18	(BOL POWER(W)/ARRAY AREA(SQ FT))*PI-N
EPS3	.88889	.90025	18	ARRAY TOPOLOGY--B=0, F=1, M=2'
LIFE	50.66667	36.65419	18	DESIGN LIFE
NHARD	5.33333	2.11438	18	NUCLEAR HARDENING--G,L=4, E=7, W=10
LAUNCH	.22222	.42779	18	LAUNCH METHOD--ELV=0, S,D=1
QUALS	27.77778	42.77926	18	QUALITY %CLASS S
APOGEE	7611.92278	7105.93313	18	ORBITAL APOGEE*DESIGN LIFE*(%QUALITYS+ .
DESIGN	2.83556	2.66150	18	DESIGN LIFE/(%QUALITYS + .1%QUALITYB)
STRUC	6.57889	7.90818	18	%DEPLOYED WT
THERM	29.27778	14.43042	18	MAX TEMP-MIN TEMP
TTC	8.02778	21.62819	18	AUTON OPS(DAYS)

CORRELATION MATRIX:

	ACS1	ACS2	ACS3	AKM1	AKM2	COMM	EPS1	EPS2	EPS3	LIFE	NHARD	LAUNCH
ACS1	1.00000											
ACS2	.38550	1.00000										
ACS3	.29354	.47809	1.00000									
AKM1	-.30217	-.26843	-.15520	1.00000								
AKM2	-.24487	-.14263	-.12000	.97472	1.00000							
COMM	.44999	.37127	.38874	.06454	.18934	1.00000						
EPS1	-.06576	.23176	.23912	-.26229	-.22356	.02812	1.00000					
EPS2	-.25068	-.03874	-.44656	.40965	.36260	-.28714	.12128	1.00000				
EPS3	.61704	.54308	.28398	-.12834	.01830	.55171	.25169	-.27934	1.00000			
LIFE	.46405	.15256	.41012	.09275	.12223	.72463	-.04957	-.20622	.35177	1.00000		
NHARD	.14378	-.04336	.07255	.15846	.20467	.20594	-.04855	-.13288	.26783	.15636	1.00000	
LAUNCH	.48178	.28571	.23905	-.00267	.12952	.84244	.13605	-.27336	.67884	.68026	.43355	1.00000
QUALS	.36922	.03571	.29881	.13458	.18293	.49788	.00370	-.33262	.39034	.35513	.34684	.28571
APOGEE	.42854	.04323	.37654	.11625	.13843	.74612	-.05071	-.21677	.25538	.97487	.19847	.68826
DESIGN	-.04679	.13961	.17905	.19967	.20580	.19750	-.20184	.13746	-.18680	.37812	-.36885	.10425
STRUC	.26185	.42244	.38244	-.32356	-.21430	.37088	.79296	-.14776	.61752	.02634	.01466	.35965
THERM	.74082	-.28576	-.52263	.03292	.05043	.11649	-.01330	-.04055	.17413	.18348	.39548	.38581
TTC	.55261	.01362	.17081	-.19771	-.21186	.14497	.05820	-.17480	.21013	.52257	.46615	.38711

Figure 2.4 Initial Factor Analysis

- F A C T O R   A N A L Y S I S -

	QUALS	APOGEE	DESIGN	STRUC	THERM	TTC
QUALS	1.00000					
APOGEE	.41338	1.00000				
DESIGN	-.50206	.30933	1.00000			
STRUC	.25222	.00079	-.22637	1.00000		
THERM	.14780	.25711	-.25892	-.10686	1.00000	
TTC	.24707	.53982	-.10850	-.12369	.50835	1.00000

1-TAILED SIG. OF CORRELATION MATRIX:

' . ' IS PRINTED FOR DIAGONAL ELEMENTS.

	ACS1	ACS2	ACS3	AKM1	AKM2	COMM	EPS1	EPS2	EPS3
ACS1	.								
ACS2	.05706	.							
ACS3	.11856	.02238	.						
AKM1	.11148	.14074	.26930	.					
AKM2	.16371	.28618	.31765	.00000	.				
COMM	.03048	.06464	.05563	.39958	.22588	.			
EPS1	.39772	.17738	.16963	.14652	.18627	.45590	.		
EPS2	.15785	.43936	.03160	.04568	.06960	.12399	.31583	.	
EPS3	.00319	.00993	.12672	.30589	.47127	.00881	.15684	.13081	.
LIFE	.02619	.27281	.04548	.35716	.31449	.00033	.42256	.20583	.07614
NHARD	.28461	.43218	.38761	.26500	.20763	.20616	.42614	.29957	.14130
LAUNCH	.02146	.12521	.16971	.49580	.30424	.00001	.29520	.13619	.00098
QUALS	.06579	.44606	.11420	.29722	.23375	.01775	.49619	.08872	.05464
APOGEE	.03800	.43238	.06176	.32299	.29191	.00019	.62081	.19379	.15321
DESIGN	.42686	.29030	.23858	.21350	.20631	.21606	.21094	.29325	.22898
STRUC	.14695	.04037	.05864	.09513	.19658	.06486	.00006	.27923	.00316
THERM	.16787	.12517	.01303	.44842	.42124	.32265	.47911	.43655	.24477
TTC	.00870	.47892	.24900	.21581	.19937	.28300	.44019	.24392	.20132

	LIFE	NHARD	LAUNCH	QUALS	APOGEE	DESIGN	STRUC	THERM	TTC
LIFE	.								
NHARD	.26777	.							
LAUNCH	.00095	.03613	.						
QUALS	.07406	.07925	.12521	.					
APOGEE	.00000	.21492	.00079	.04408	.				
DESIGN	.06091	.07797	.34030	.01687	.10582	.			
STRUC	.45869	.47698	.07134	.15632	.49875	.18319	.		
THERM	.23386	.05214	.05691	.27918	.15151	.14976	.33650	.	
TTC	.01304	.02617	.05625	.16148	.01038	.33612	.31243	.01562	.

Figure 2.4 Initial Factor Analysis (Continued)

At this point the objective in eliminating variables became to maximize the percentage of variance explained.[12] In addition to large loadings on their principal factors, ACS1, TTC and LAUNCH had significant loadings in other columns. By trying various combinations it was found that by eliminating ACS1 and TTC but retaining LAUNCH the variance explained reached a maximum of 81.7%.[13] A scree plot of the eigenvalues and the final rotated factor matrix are shown in Figure 2.5 on page 56.

Factor Interpretation

The clustering of the variables and the strong loadings lead quite easily to conclusions as to the nature of the four factors that describe the technology embedded in a satellite.

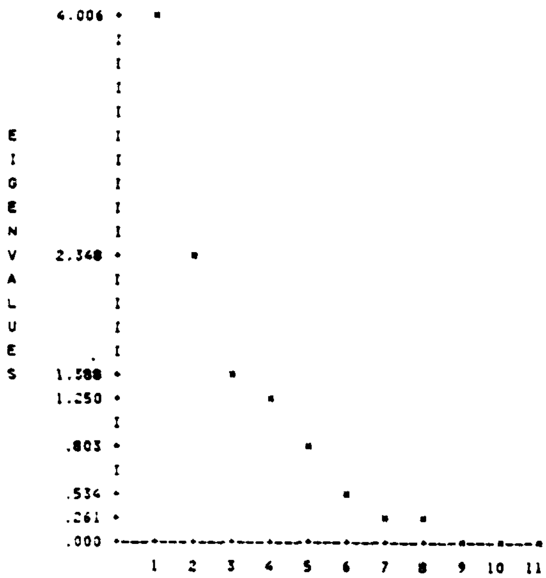
FACTOR 1 can be described as MISSION. To describe mission, the requirements must be specified in terms of APOGEE, LIFE, COMM and LAUNCH:

APOGEE -- (Orbital apogee * Design life * (% Quality S + 0.8 % Quality B) / 10000) -- Add to LIFE a description of the required apogee and quality levels, in percentages S and B.

LIFE -- What must the design life of the satellite be?

COMM -- While the variable is actually required power for communications equipment, it should be easily estimable from mission specifications.

LAUNCH -- How will the satellite be launched?



PC EXTRACTED 4 FACTORS.

VARIMAX ROTATION 1 FOR EXTRACTION 1 IN ANALYSIS 1 - KAISER NORMALIZATION.

VARIMAX CONVERGED IN 6 ITERATIONS.

ROTATED FACTOR MATRIX:

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4
APOGEE	.96321	.03372	-.08906	.12060
LIFE	.95995	.03276	.00152	.04565
COMM	.83905	.13307	.36626	.06161
LAUNCH	.73758	.04849	.42788	.41891
AKM2	.08684	.98019	-.04653	.08201
AKM1	.03698	.96110	-.20146	.05165
ACS2	.16682	-.08000	.80553	-.32373
EPS3	.34378	.01273	.78218	.25341
EPS1	-.12843	-.27471	.53792	.07218
THERM	.16552	-.08660	-.15751	.84639
NHARD	.09169	.21310	.17057	.76016

Figure 2.5 Scree Plot and Rotated Factor Matrix

FACTOR 2 is an indirect measure, ORBITAL. The apogee kick motor is used in obtaining the correct orbit. If the designer knows the MISSION, the launch method, and the required apogee and shape of the orbit, rough specification of the two AKM variables should not be difficult:

AKM2 -- Propellent weight / Dry weight.

AKM1 -- Specific impulse.

FACTOR 3 is an indirect description of the electrical power system technology.

EPS3 -- Array topology.

EPS1 -- Battery Capacity.

Note that,

ACS2 -- Primary stabilization method,

is integrally related to array topology due to its implications for array deployment. Therefore, these three variables make up a single factor we can label ELECTRICAL POWER.

FACTOR 4 is a description of the ENVIRONMENT. Two environmental variables load on this factor:

THERM -- Max temperature - Min temperature.

NHARD -- Nuclear hardening.

The temperature range affects component design.[14] The required level of nuclear hardening is mission-determined. The most logical interpretation is ENVIRONMENT because these variable values result from the environment in which the mission must be conducted.

To recap, there are four factors that describe the technology embedded in a satellite and, together, account for 81.7% of the variance in the sample:

FACTOR	LABEL	VARIABLES
1	MISSION	APOGEE, LIFE, COMM, LAUNCH
2	ORBITAL	AKM2, AKM1
3	ELECTRICAL POWER	EPS3, ACS2, EPS1
4	ENVIRONMENT	THERM, NHARD

These variables should be ascertainable during the early decision-making stages of the system life-cycle, thereby conform with the requirement set in Dodson's third criterion.[15]

Factor Scores

The next step was to construct a table of factor scores for all eighteen systems.[16] The four scores for each of the 18 systems, in A through R order, are shown in Table 2.1 on page 59.

Recall that THERM was missing for System R. In calculating the factor scores for System R the sample average value of THERM was used.

ELLIPSOID CONSTRUCTION

Dodson's most important contribution to the development of SOA theory has been the ellipsoid method of technology specification.[17] Seen in two dimensions, the ellipsoid model is

Table 2.1 Factor Scores

System	Fact 1	Fact 2	Fact 3	Fact 4
	--------- Factor Scores ---------			
A	0.5481	1.4894	1.4514	1.3038
B	-0.7021	-0.6149	0.8253	-0.8771
C	1.4523	-1.1906	0.3233	2.3646
D	-0.2591	1.1941	0.8042	0.0857
E	-0.8919	-0.7342	0.4668	-0.6761
F	-0.5195	0.6648	-1.3337	0.8363
G	-0.2870	-1.3133	-1.7576	0.8937
H	0.4619	-0.8923	-0.4650	-1.1932
I	2.1776	-1.0966	0.4696	-0.3093
J	-1.4171	-1.0918	1.5999	-0.0233
K	-1.0725	0.9872	0.2058	0.4739
L	-0.9641	-0.6474	0.0670	-0.2184
M	-0.1629	-0.8299	0.2157	-0.4064
N	-1.1595	0.7442	-1.0434	1.0676
O	0.6814	0.9718	-0.4915	-1.6992
P	0.1755	0.7231	-0.4819	-0.8667
Q	0.7529	0.4861	-1.7235	-0.4232
R	1.1859	1.1505	0.8674	-0.3126

relatively simple. (See Figure 2.6 on page 60.)[18] Two system attributes are scaled on X_1 and X_2. The ellipse represents a particular level of technology or SOA. Point A lies on the ellipse. The general idea is that if mission requirements call for more X_1 the need could be met by moving to the right along the curve, thereby giving up some X_2. Note SOA is <u>not</u> increased. The curve can be thought of as an iso-SOA curve.

The SOA curve exhibits diminishing returns. In order to obtain more X_1 ever-increasing quantities of X_2 must be given up. This is a common phenomenon in design.[19]

Dodson suggests that (in N-space) a new hypersurface is required for each SOA. In this study, however, only one

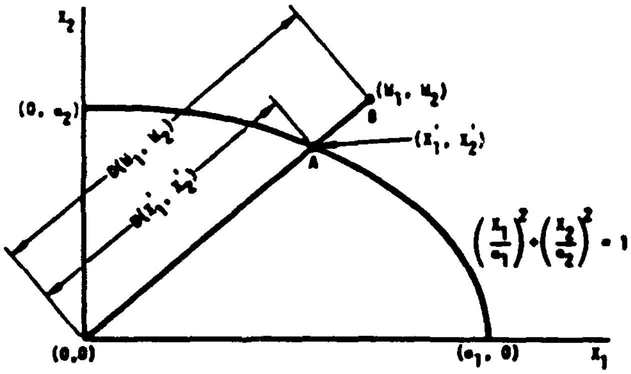


Figure 2.6 Dodson's Ellipsoid Model, Two Dimensions

ellipsoid was constructed for the entire sample. Therefore, it can be thought of as a technology hypersurface rather than representing a static SOA.[20]

Each system plots in N-space as a point. The proportional radial distance from the origin represents the level of technology embodied in that particular system. Thus, Point B is more technologically advanced than Point A (or any other point lying on the "average technology level" curve). The procedure standardizes the distance from the origin to the curve as one, so $D(W_1, W_2)$ is greater than one indicating it represents an SOA higher than the average technology for the type of systems under study, satellites.

Factor scores result from a calculation that uses variable values expressed as standardized normal deviates. Therefore many factor scores are negative. Obviously negative point values cannot be used in constructing an ellipsoid. The procedure

followed was to add an arbitrary constant, three, to each factor score, thereby looking at values from a point three standard deviations below the mean rather than from the mean. Note that factor scores represent a particular blend of the four parameters affecting the level of technology in a system. The technology level itself is a function of the four scores.

The modified factor scores were entered in a computer program designed to produce ellipsoid parameters and point values.[21] The program is listed and the relevant run is shown over the next three pages. The desired overall technology values are shown in the column headed "MU-J", but it is important to remember that each system has coordinates on four factor attributes as well as a distance from the origin.

Output

The final equation for the ellipsoid representing satellite technology is,

$$\frac{X_1^2}{6.9446^2} + \frac{X_2^2}{6.2728^2} + \frac{X_3^2}{6.1338^2} + \frac{X_4^2}{7.3472^2} = 1$$

where,

X_i is the factor score (plus three) for the ith factor

There is no statistically rigorous methodology for determining adequate sample sizes in ellipsoid construction. The objective, of course, is to achieve stability of the surface in

```
1 LPRINT
2 LPRINT
3 LPRINT "NOTE: DATA ARE CONTAINED IN DATA STATEMENTS LOCATED IN LINES"
4 LPRINT "330-410 OF THIS PROGRAM.  LIST LINES 10-80 FOR INSTRUCTIONS."
5 LPRINT
6 LPRINT
10 'This program fits the best ellipsoid surface, using proportional
20 'distances along radials.  The input data are contained in data
30 'statements and consists of: first line: MB, NB, where,
40 '          MB = the number of data sets entered and
50 '          NB = the number of variables in each set.
60 'Subsequent lines: DAT(L,J), where,
70 'DAT(L,J) is the value of the Jth variable in the Lth set.
80 'The maximums are MB = 20, NB = 6.
90 '
100 '
110 DIM AB(6,5),BB(6),CB(20),DAT(20,5),SDAT(20,6),INDEX(6,3)
120 READ MB, NB
130 FOR I = 1 TO MB
140   FOR J = 1 TO NB
150     READ DAT(I,J)
155 DAT(I,J) = DAT(I,J)+3
160     SDAT(I,J) = DAT(I,J)
170   NEXT J
180 NEXT I
190 FOR I = 1 TO NB
200   BB(I) = 0
210   FOR J = 1 TO NB
220     AB(I,J) = 0
230   NEXT J
240 NEXT I
250 FOR K = 1 TO NB
260   FOR J = 1 TO MB
270     BB(K) = BB(K) + SDAT(J,K)
280     FOR I = 1 TO NB
290       AB(K,I) = AB(K,I) + SDAT(J,K) * SDAT(J,I)
300     NEXT I
310   NEXT J
320 NEXT K
330 DATA 18,4
350 DATA .54810, 1.4894, 1.45142, 1.20375
360 DATA -.70209, -.61494, .82570, -.87712
370 DATA 1.45234, -1.14053, .22374, 2.36461
380 DATA -.25912, 1.17413, .50042, .08567
390 DATA -.99189, -.71423, .46678, -.67615
400 DATA -.51923, .56461, -1.22373, .82629
401 DATA -.26698, -1.21331, -1.75764, .87370
402 DATA .46188, -.89210, -.46497, -1.19317
403 DATA 2.17764, -1.09660, .45959, -.30929
404 DATA -1.41706, -1.09164, 1.59987, -.02226
405 DATA -1.07248, .98715, .20581, .47392
406 DATA -.9641, -.64742, .06703, -.21844
407 DATA -.16785, -.82989, .21575, -.40637
408 DATA -1.15952, .74422, -1.04336, 1.06756
409 DATA .68137, .97182, -.49150, -1.64919
410 DATA .17552, .72205, -.48186, -.85670
411 DATA .75285, .48610, -1.7225, -.42022
412 DATA 1.18592, 1.15048, .86742, -.31258
420 GOSUB 800
430 IF D < .00001 THEN 770 ELSE 440
440 LPRINT "                                    ELLIPSOID FIT"
450 LPRINT
460 LPRINT "                                     PARAMETERS"
470 LPRINT
480 LPRINT "          NUMBER                LINEAR FORM           ELLIPSOID FORM
490 FOR K = 1 TO NB
500   SQ = SQR(1/BB(K))
510 LPRINT "             ";K;"               ";BB(K);"              ";SQ
520 NEXT K
530 LPRINT
540 LPRINT "                                     FIT"
550 LPRINT
560 LPRINT "        SAMPLE POINT               MU-J                (MU(J-1)SQ."
570 SSE = 0
580 FOR K = 1 TO MB
590   CB(K) = 0
600   FOR J = 1 TO NB
610     CB(K) = CB(K) + SDAT(K,J)*BB(J)
620   NEXT J
630   SQ = (CB(K)-1)^2
640   SSE = SSE + SQ
650 LPRINT "             ";K;"               ";CB(K);"              ";SQ
```

Figure 2.7 Ellipsoid Program

```
660 NEXT K
670 LPRINT
680 LPRINT "FIT STATISTIC = ";SQR(SSE/(MB-NB));"  DEGREES OF FREEDOM = ";MB-NB
690 LPRINT
700 LPRINT
710 LPRINT "     SAMPLE"
720 LPRINT "OBSERVATION: X1, X2, X3, X4, X5, X6"
730 FOR I = 1 TO MB
740 LPRINT I;DAT(I,1);DAT(I,2);DAT(I,3);DAT(I,4);DAT(I,5);DAT(I,6)
750 NEXT I
760 GOTO 780
770 LPRINT "DETERMINANT = 0"
780 REM
790 STOP
800 N = NB
810 D = 1
820 FOR J = 1 TO N
830   INDEX(J,3) = 0
840 NEXT J
850 FOR I = 1 TO N
860   AMAX = 0
870   FOR J = 1 TO N
880     IF INDEX(J,3) = 1 THEN 970 ELSE 890
890     FOR K = 1 TO N
900       IF INDEX(K,3) > 1 THEN 1410 ELSE 910
910       IF INDEX(K,3) = 1 THEN 960 ELSE 920
920       IF AMAX >= ABS(AB(J,K)) THEN 960 ELSE 930
930       IROW = J
940       ICOLUM = K
950       AMAX = ABS(AB(J,K))
960     NEXT K
970   NEXT J
980   INDEX(ICOLUM,3) = INDEX(ICOLUM,3) + 1
990   INDEX(I,1) = IROW
1000   INDEX(I,2) = ICOLUM
1010   IF IROW = ICOLUM THEN 1110 ELSE 1020
1020   D = -D
1030   FOR L = 1 TO N
1040     SW = AB(IROW,L)
1050     AB(IROW,L) = AB(ICOLUM,L)
1060     AB(ICOLUM,L) = SW
1070   NEXT L
1080   SW = BB(IROW)
1090   BB(IROW) = BB(ICOLUM)
1100   BB(ICOLUM) = SW
1110   PIVOT = AB(ICOLUM, ICOLUM)
1120   D = D*PIVOT
1130   AB(ICOLUM,ICOLUM) = 1
1140   FOR L = 1 TO N
1150     AB(ICOLUM,L) = AB(ICOLUM,L)/PIVOT
1160   NEXT L
1170   BB(ICOLUM) = BB(ICOLUM)/PIVOT
1180   FOR L1 = 1 TO N
1190     IF L1 = ICOLUM THEN 1260 ELSE 1200
1200     T = AB(L1, ICOLUM)
1210     AB(L1, ICOLUM) = 0
1220     FOR L = 1 TO N
1230       AB(L1,L) = AB(L1,L) - AB(ICOLUM,L)*T
1240     NEXT L
1250     BB(L1) = BB(L1) - BB(ICOLUM) * T
1260   NEXT L1
1270 NEXT I
1280 FOR I = 1 TO N
1290   L = N + 1 - I
1300   IF INDEX(L,1) = INDEX(L,2) THEN 1380 ELSE 1310
1310   JROW = INDEX(L,1)
1320   JCOLUM = INDEX(L,2)
1330   FOR K = 1 TO N
1340     SW=AB(K,JROW)
1350     AB(K,JROW)=AB(K,JCOLUM)
1360     AB(K,JCOLUM)=SW
1370   NEXT K
1380 NEXT I
1390 FOR K = 1 TO N
1400   IF INDEX(K,3) = 1 THEN 1430 ELSE 1410
1410   ID = 2
1420   GOTO 1460
1430   REM
1440 NEXT K
1450 ID = 1
1460 RETURN
1470 END
```

Figure 2.7 Ellipsoid Program (Continued)

```
NOTE: DATA ARE CONTAINED IN DATA STATEMENTS LOCATED IN LINES
370-410 OF THIS PROGRAM.  LIST LINES 10-80 FOR INSTRUCTIONS.

                         ELLIPSOID FIT

                          PARAMETERS

        NUMBER            LINEAR FORM          ELLIPSOID FORM
          1               2.072505E-02              6.944604
          2               .0254146               6.272756
          3               .0265789               6.133827
          4               1.852507E-02              7.34717

                              FIT

      SAMPLE POINT            MU-J             (MUJ-1)SU.
          1                 1.643049                .4135114
          2                 .7264728                7.481713E-02
          3                 1.320927                .1029943
          4                 1.163864                .0268513
          5                 .6431013                .1280915
          6                 .8153473                3.409666E-02
          7                 .5439248                .2080046
          8                 .592587                .1559039
          9                 1.102019                1.040765E-02
          10                 .8710202                1.663579E-02
          11                 .9777861                4.93459E-04
          12                 .6199539                .1444351
          13                 .6860623                9.855686E-02
          14                 .8347822                2.729693E-02
          15                 .8805318                1.427267E-02
          16                 .9142096                3.451806E-02
          17                 .7672041                5.419393E-02
          18                 1.322453                .1105252

FIT STATISTIC =  .344923   DEGREES OF FREEDOM =  14


   SAMPLE
OBSERVATION: X1, X2, X3, X4, X5, X6
 1  3.5481  4.4894  4.45142  4.70375  0  0
 2  2.23791  2.38506  3.8253  2.72088  0  0
 3  4.45234  1.80937  3.32334  5.36461  0  0
 4  3.74088  4.19413  3.8042  3.08567  0  0
 5  2.10811  2.26577  3.46678  2.32385  0  0
 6  2.48047  3.66481  1.66627  3.83629  0  0
 7  .71702  1.68669  1.34236  3.8737  0  0
 8  3.46188  2.1077  2.53503  1.80683  0  0
 9  5.13764  1.9034  3.46959  2.69071  0  0
 10  1.58394  1.90816  4.59987  2.97674  0  0
 11  1.92752  3.98715  3.20583  3.47392  0  0
 12  2.0359  2.35258  3.06703  2.78156  0  0
 13  2.83715  2.17011  3.21575  2.59363  0  0
 14  1.84047  3.74422  1.95664  4.06756  0  0
 15  3.68137  3.97182  2.5085  1.30081  0  0
 16  3.17552  3.72305  2.51814  2.1333  0  0
 17  3.75286  3.4861  1.2765  2.57678  0  0
 18  4.18592  4.15048  3.86742  2.68742  0  0
```

Figure 2.8 Ellipsoid Program Output

hyperspace. (An intuitive definition of stability is that little change in the positioning of the ellipsoid would result from adding another data point.) The author has constructed ellipsoids from a number of data bases and, while there is obviously some variation from case to case, reasonable stability is usually achieved when the number of observations in the sample is at least four times the number of variables per observation. This rule of thumb is recommended as a guideline. In the case at hand there were four factors and 18 systems, so the sample size guideline was met.

ANALYTICAL SUMMARY

Before discussing the results it might be useful to summarize the steps taken:

1. The 85 variables used by the Air Force to describe satellite technology were studied by engineers to separate those which are design objectives from those which are simply byproducts of the design. The result was 18 relevant variables or composite variables constructed so as to observe Dodson's three criteria.

2. Factor analysis was used to take advantage of redundancies in the data, thereby clustering variables onto four "factors". Thus, the information content of 18 technology describers was condensed down to four factor scores for each satellite.

3. The factor scores formed the basis for determining a technology ellipsoid for satellites. The point position of each individual satellite was used to calculate a proportional distance from the origin, which is a <u>single</u> measure of SOA.

The steps are summarized in Figure 2.9 below:

Input	==>	[Process]	==>	Output
85 variables	==>	[expert judgement]	==>	18 relevant variables
18 relevant variables	==>	[factor analysis]	==>	4 factor scores
4 factor scores	==>	[ellipsoid method]	==>	A <u>single</u> technology measure containing much information

Figure 2.9 Summary of Analytic Steps

<u>Results</u>

The validity of this method can be seen in several ways. First, consider a chronological plot of SOA by satellite. (See Figure 2.10 on page 67.) The dates shown on the horizontal axis in the graph are the years in which the 18 satellites studied were first launched. The SOA measure is on the vertical axis. For several years, from 1966 through 1977, satellite technology remained relatively constant. Some particular systems were more "advanced" than others, but the SOA was essentially fixed. Then, in about 1978, SOA began rising. The overall picture this presents is clearly consistent with a "new" technology just beginning to enter the accelerating portion of its S-curve.[22]

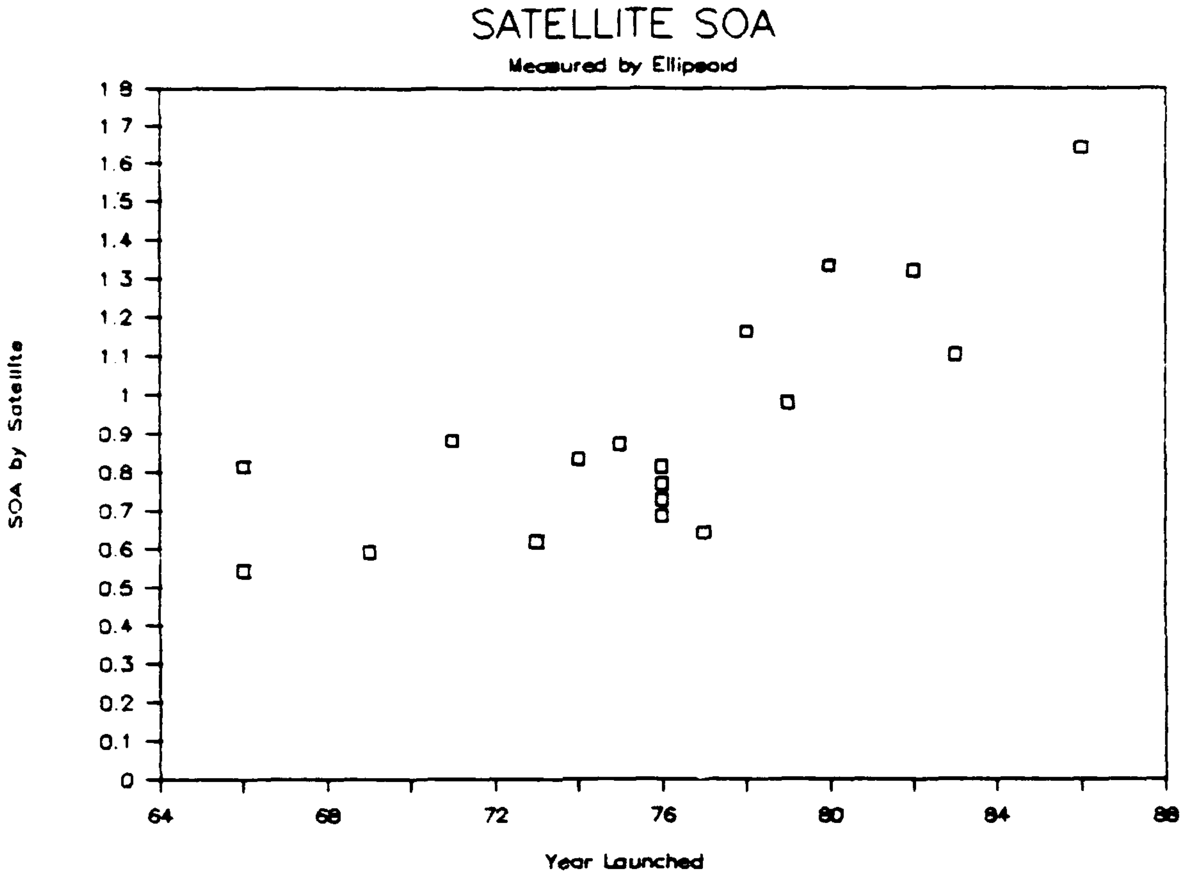


Figure 2.10 Satellite SOA Through Time

Another way to examine the growth in satellite technology during the twenty years represented is to use Leinhard's method to calculate the growth rate and to compare the observed growth rate for satellites with that of other technologies.[23]

Begin by plotting ln(SOA) against time. (See Figure 2.11 on page 68.) A regression fit to this data form is highly significant (but does have a rather large standard error). The equation is,

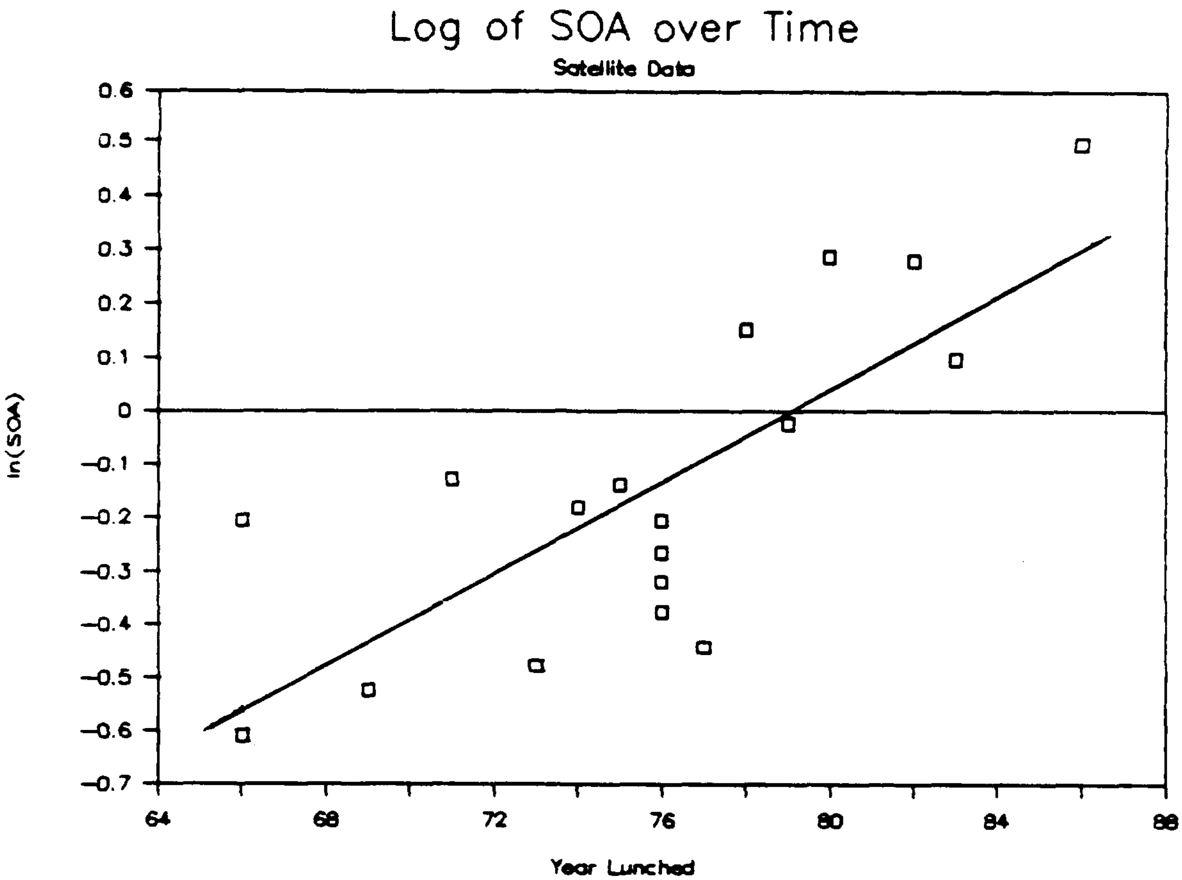


Figure 2.11 Log form of SOA Through Time

$$\ln(SOA) = -3.44967 + 0.043662\ (Year - 1900)$$

$$t = 4.86$$

$$\text{significance} = .001$$

Variance explained (R^2)	.596
Adjusted R^2	.571
Standard error of the estimate	.201

Lienhard's equation shows satellite technology has grown at a 30-year _n_-folding of 3.71: the "time constant," _T_ is 22.9 years for an _e_-folding. This means satellite technology is

growing faster than the thermal efficiency of steam power did from 1742-1850, but somewhat more slowly than the speed of air transport from 1884-1967.

It is also instructive to examine the breakdown of scores on the individual factors through time. The following graph looks at three time intervals, 1966-74, 1975-77 and 1978-83, plotting the four average (by satellite) factor scores during each.

The average SOA measure for the 1966-74 systems was 0.715; the average for 1975-77 was insignificantly higher, 0.751. But the composition of factor scores, or the coordinates of the

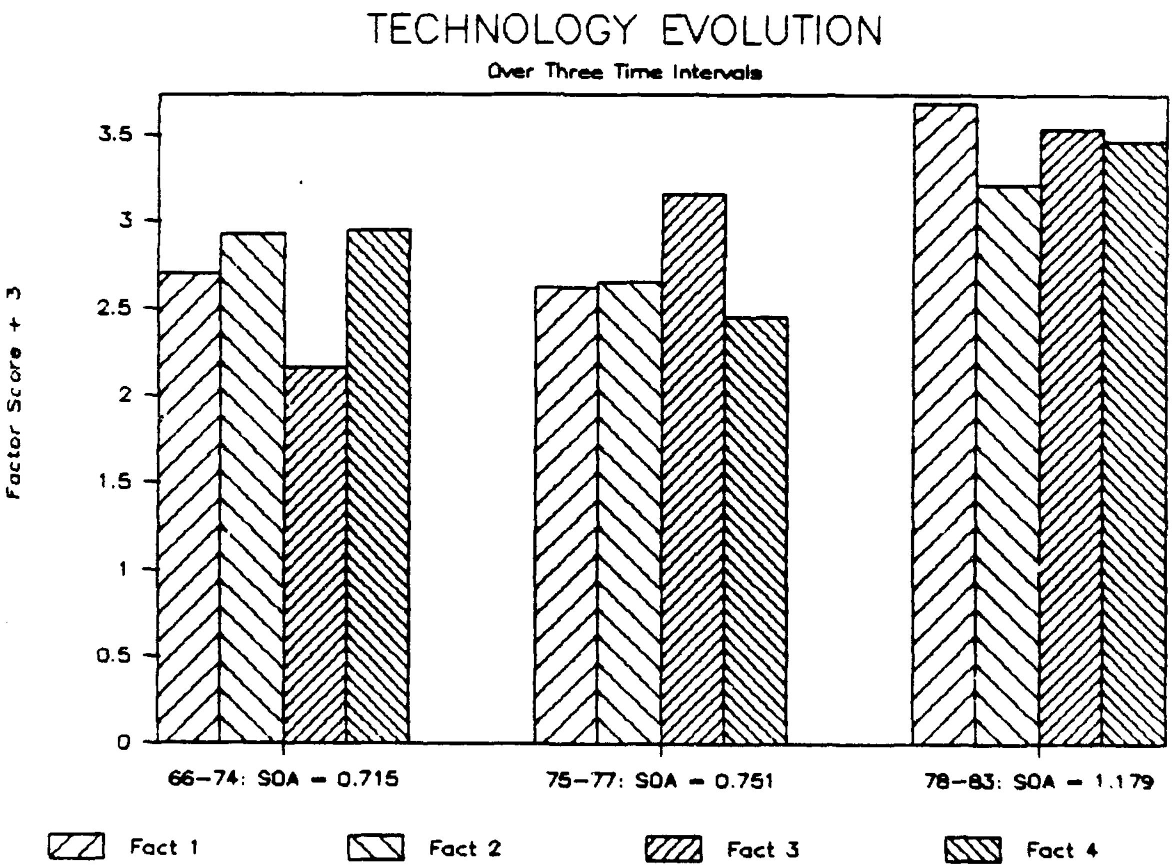


Figure 2.12 Factor Score Growth, 1966-1983

representative points on the ellipsoidal hypersurface are different. During 1975-77 considerably more emphasis was placed on advanced electrical power systems, Factor 3.

The satellites launched during 1978-83 were more advanced in all four factors, and the average SOA measure was considerably higher, 1.179. The one satellite launched in 1986 is not included in the last group, but its SOA was even higher, 1.643. It's score on the <u>mission</u> factor was comparable to the 1978-83 group, but it was considerably more advanced in the <u>orbital</u>, <u>electrical power</u> and <u>environment</u> factors.

Still another way to view the progress in SOA is to look at the average level embodied in all satellites launched each year. That approach is taken in the graph below. (See Figure 2.13 on page 71.) Again, we see the upward curving shape so typical of the low end of an S-curve.

<u>Chapter Objective Revisited</u>

The objective of this Chapter was to provide technology measures that will be useful in determining development cost. Operationally, if one knows the status of technology at the onset of a development project, and the desired design characteristics the new system to be developed, one (hopefully) will be in a position to estimate the development cost to be incurred. ... will be addressed in the next chapter. This ... the SOA measures to be tested.

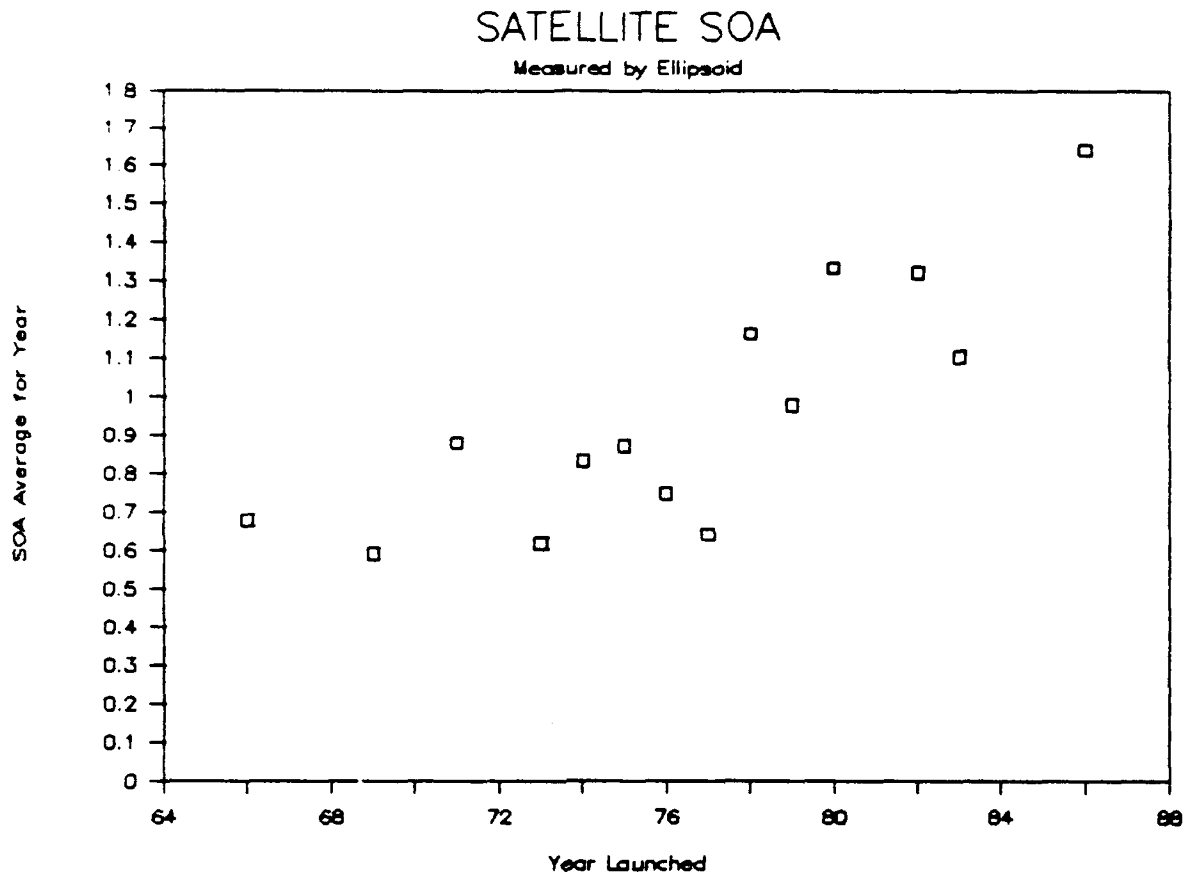


Figure 2.13 Average Annual SOA Through Time

ENDNOTES

1. See Dodson, E. N., "A General Approach to Measurement of the State of the Art and Technological Advance," Technological Forecasting, 1 (1970), pp. 391-408. By "theoretically correct" I mean the method conforms with Grosch's Law. For a discussion of Grosch's Law and its application to technology measurement see Knight, K. E., "A Functional and Structural Measurement of Technology," Technological Forecasting and Social Change, 27, (1985), pp. 107-127.

2. See Gordon, T. J., and T. R. Munson, "A Proposed Convention for Measuring the State of the Art of Products or Processes," Technological Forecasting and Social Change, 20 (1981), pp. 1-26.

3. Alexander, A. J., and J. R. Nelson, "Measuring Technological Change: Aircraft Turbine Engines," Report No. R-1017-ARPA/PR, The RAND Corporation (Santa Monica, June, 1972), 37 pgs.

4. From Dodson, E. N., Parametric Cost Analysis: General Procedures and Extensions, Technical Memorandum 1993, General Research Corporation (Santa Barbara, 1976), p. 25.

5. These data were supplied by Headquarters, Space Division (AFSC), Los Angeles Air Force Station, P.O. Box 92960, Los Angeles, CA 90009-2960. While the data are not classified, the author was asked not to identify specific satellites by name or designator. To honor this request the systems will be referred to only by randomly-assigned code letters. This researcher is particularly indebted to Captain Blain Webber, USAF, for his assistance and cooperation.

6. A complete listing of the original data is not provided here. DoD agencies will be provided copies of the complete data upon request.

7. Dodson, E. N., and C. A. Graver, An Approach to Quantitative measurement of Advances in State of the Art, Internal Memorandum (Releasable) (Santa Barbara: General Research Corporation, January 1969), p. 13.

8. Ibid.

9. Ibid., p. 14.

10. The mean value of THERM was inserted to avoid distorting later portions of the analysis.

11. For an excellent summary of variable selection criteria and "simple" structure objectives see Kerlinger, Fred N., Foundations of Behavioral Research, 2nd ed. (New York: Holt, Rinehart and Winston, 1973), pp. 672-73.

12. This is a common practical expedient in factor analysis. See Harman, Harry H., Modern Factor Analysis, 3rd ed. (Chicago: University of Chicago, 1976), p.185.

13. Of course, this method is not an optimization method. In general, no optimization methods exist for factor analysis. There is no guarantee that a superior solution could not be reached by some other sequence of steps. The author can only report the steps taken in this particular analysis.

14. In designing satellites one has a choice of increasing the tolerable temperature range or increasing the sophistication of the temperature control devices. It was not at first obvious whether to use temperature range or its reciprocal as a variable. However, the range itself had the positive correlation, so the temperature tolerance of components must be more representative of embodied level of technology.

15. Op. cit.

16. The SPSS^{x} regression method was used to determine factor scores. Alternates are the Bartlett method and the Anderson-Rubin method. See Lawley, D. N. and A. E. Maxwell, Factor Analysis as a Statistical Method (New York: American Elsevier, 1971), p. 5 and Chap. 8.

17. See op. cit., "A General Approach to Measurement of the State of the Art and Technological Advance," Technological Forecasting, Vol. 1, (1970), pp. 391-408.

18. This figure is taken from Dodson, ibid., p. 400.

19. This property is described in more rigorous terms by Grosch's Law. See Knight, K. E., "A Functional and Structural Measurement of Technology," Technological Forecasting and Social Change, 27, (1985), pp. 107-127.

20. This representation should be allowable as a result of the assumption of continuity. See Alexander and Nelson, op. cit.

21. The program used was adapted from one listed in the Dodson internal memorandum, op. cit., Appendix I. Dodson's program was written in FORTRAN and was based in part on a matrix inversion subroutine contained in McCormick, J. M. and M. Salvadori, Numerical Methods in FORTRAN (New York: Prentice-Hall, 1964), Program 9-7. The program was recoded by the author in BASIC for an IBM PC.

22. A good treatment of S-curves as a method of measuring SOA advance can be found on pages 18-24 of Gordon, T. J. and T. R. Munson, "A Proposed Convention for Measuring the State of the Art of Products or Processes", Technological Forecasting and Social Change, Vol. 20 (1981), pp. 1-26.

23. Lienhard, J. H., "The Rate of Technological Improvement before and after the 1830s," Technology and Culture, (July 1979), pp. 515-530. See especially pp. 516-517, but note that Leinhard's Equation (1) contains typos. For a correct version of his Equation (1) see page 29 of this report.

Chapter 3

COST ESTIMATION AND CONTROL

INTRODUCTION

The end purpose of developing SOA measures is to expedite prediction of the cost of developing new technological systems, which is the initial step in any attempt to control such costs. It is therefore fitting to search for statistical associations (if any) between the degree to which a system's technology has been extended through successive development efforts and the level of activity required to bring these extensions about.

SOA EXTENSION CONCEPTS

The definition and measurement of the amount of change represented by a particular technological development requires careful consideration. In Chapter 2 the level of technology embodied in each of 18 satellites was determined, and each was expressed in terms of a point in hyperspace, but the concept of an SOA *extension* was not articulated.

An SOA *extension* involves the movement of technology from one point to another. If at the outset of a particular development project the technological *objective* of the project can be specified as a point in hyperspace, and if the *closest*

existing technology can also be identified as a point, then the development task at hand can be defined by referencing the technological distance separati ~ the two.[1] This is simply the Euclidian distance between the ~s.

Consider first a mathematica ement of technological distance:

$$d_{ij} = \sqrt{\sum_{k=1}^{N} (S_{ik} - S_{jk})^2}$$

where,

d_{ij} = the technological distance between the ith and jth systems,

S_{ik} = a technological attribute score of the ith system on the kth attribute,

S_{jk} = a technological attribute score of the jth system on the kth attribute,

N = the number of technological attributes used to define SOA for systems of this type.

Several more detailed measurement concepts will now be discussed. These ideas are most easily illustrated in two dimensions, but they are clearly generalizable to N-dimension settings.

Consider the graph shown in Figure 3.1 on page 77. In 1985 Martino measured the technology embodied in numerous aircraft designs by making use of three indexed variables, structural

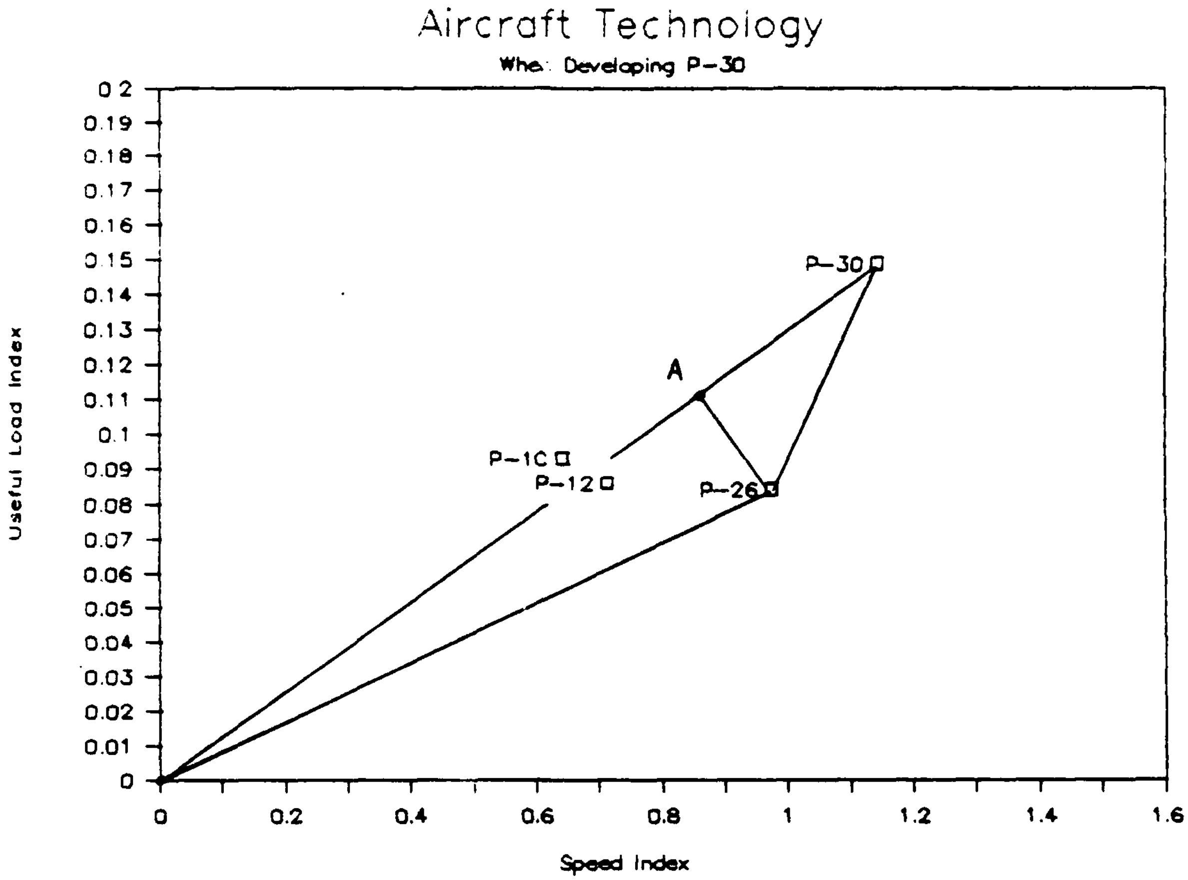


Figure 3.1 SOA Extension Illustration

efficiency, maximum speed and useful load.[2] To keep the discussion in two-dimensional space let us consider only the useful load and speed indices. Points representing four aircraft, the P-1C, P-12, P-26 and P-30 are shown on the graph.

Consider the moment in time when development of the P-30 was initiated. Designers would begin their task with a technological experience base represented, in this simplified illustration, by the three predecessor aircraft. We can locate all three predecessors as well as the performance objectives of this development effort--symbolized by the P-30's coordinates.

What is the technological distance to be spanned by this development task? Geometrically, it would be the minimum radial distance to the P-30 from some other currently existent system. By calculating technological distances we can easily conclude that the "closest" predecessor technology is represented by the P-26; that distance can be symbolized as P-26 --> P-30.

Now consider three other distinct measures of technological spread. Designate these reach, advance and redesign.

Definitions

The reach of the P-26 is its distance from the origin, easily calculated from the formula for technological distance by setting $S_{jk} = 0$. Similarly, the reach of the P-30 is the distance, Origin --> P-30.

The advance represented by moving from the P-26 to the P-30 is (Origin --> P-30) - (Origin --> P-26), or the difference in the reach of the two systems, also depicted as A --> P-30.

Finally, redesign is the lateral shift associated with the changing blend of technological attributes between the two aircraft, P-26 --> A. This distance can be approximated as,

$$\sqrt{(\text{P-26} \dashrightarrow \text{P-30})^2 - (\text{A} \dashrightarrow \text{P-30})^2}$$

which is just the square root of the technological distance between the P-26 and the P-30 squared less the advance squared (by simple Euclidian geometry).

HYPOTHESES

The first hypothesis to be tested is that the difficulty of the development task, as measured by the time required for its completion, is a function of the three measures of technological spread. The advance represents the "invention" aspects of the development--the "true" SOA progress required. The redesign portion represents a different (and perhaps less demanding) aspect of the project--movement parallel to an old SOA surface. (Note that advance and redesign can be thought of as the vector components of the technological distance between the two systems.) Finally, reach measures the total technological complexity, or the overall ambition demanded by the project.

H_1: Development Time = f(Advance, Redesign, Reach)

Relevant Satellite Data

The data relevant to this portion of the analysis are shown in Table 3.1 on page 80. The reported cost figures are "nonrecurring" development costs provided by the Air Force for each system, adjusted to constant 1986 dollars by using the OSD 3600 Escalation Index of prices for development work. The "time" column reports the time elapsed, in months, from awarding the development contract to the first launch of the satellite. The figures for advance, redesign and reach were calculated as formulated above from the four factor scores reported in

Table 3.1 Data for Hypothesis Testing

System	Min Dist Predecessor	NR Cost FY86$	Devel Time(Mo)	Advance	Redesign	Reach
H	G	73594.4	25	0.01947	0.37529	0.76986
O	F	116580.0	27	0.02398	0.41191	0.93837
L	H	37228.4	32	0.01076	0.26210	0.78737
J	H	155522.8	46	0.10584	0.44910	0.93328
N	F	32585.5	28	0.00719	0.10878	0.91366
M	H	319498.7	37	0.03647	0.17506	0.82829
B	H	91707.4	37	0.05194	0.27101	0.85233
Q	F	64383.3	37	-0.01799	0.25978	0.87590
P	O	121932.3	33	-0.02440	0.13829	0.90234
E	L	108084.9	37	0.00867	0.09139	0.80131
K	N	14943.2	36	0.05180	0.21674	0.98883
R	P	180652.8	56	0.18031	0.21766	1.15432
C	M	157820.4	64	0.22497	0.38644	1.14932
I	H	451274.0	86	0.18782	0.25399	1.04977

Table 2.1 on page 59 (plus the constant, 3, to position all values in positive space).

Four satellites were excluded from Table 3.1, and from this stage of the analysis. Systems F and G were omitted because they had no chronological predecessors. That is, no satellites from the available data set had been launched prior to F and G's contract award dates. Satellite D was omitted because its contract award date was unknown. Finally, A was omitted because it was known to have been a very minor upgrade of another satellite for which data were not available. The data were complete for the remaining 14 systems, except that only the year of contract award, not the month, was known for systems R, C and I. In each case the contract was awarded in 1976. System K was also contracted in 1976--in February. The working assumption

adopted was to treat R, C, and I as being awarded in February as well, but other assumptions were analyzed for result sensitivity with very little disparity.

Test of First Hypothesis

To test the first hypothesis, a multiple regression was run. The result was,

Time = 52.86 +	218.93 Advance -	34.28 Redesign -	17.37 Reach
t statistics	(3.69)	(1.45)	(0.47)
Significance	.001	.085	.322

Variance explained (R^2)	.791
Adjusted R^2	.728
Standard error of the estimate	8.745

Taken as a whole, the regression is highly significant. Advance is by far the most important determinant of development time. Neither redesign nor reach is statistically significant.[3] Table 3.2 and Figure 3.2 on page 82 show the residuals and a plot of predicted versus actual time.

Development cost may not be a smooth function of development time. As a program drags on beyond its intended completion date, it may be relatively more costly to compress the required accomplishment into an increasingly abbreviated time horizon. Putnam has humorously but graphically illustrated the difficulty of trying to hurry development projects by adding more people in

Table 3.2 Residuals from the Time Regression

ACTUAL Time	PREDICTED Time	RESIDUAL
25	30.39	-5.39
27	27.69	-.69
[illegible]	32.56	-.56
28	34.84	-6.84
46	44.43	1.57
37	40.46	-3.46
37	40.14	-3.14
37	24.8	12.2
33	27.11	5.89
37	37.71	-.71
36	39.6	-3.6
56	64.83	-8.83
64	68.91	-4.91
86	67.04	18.96

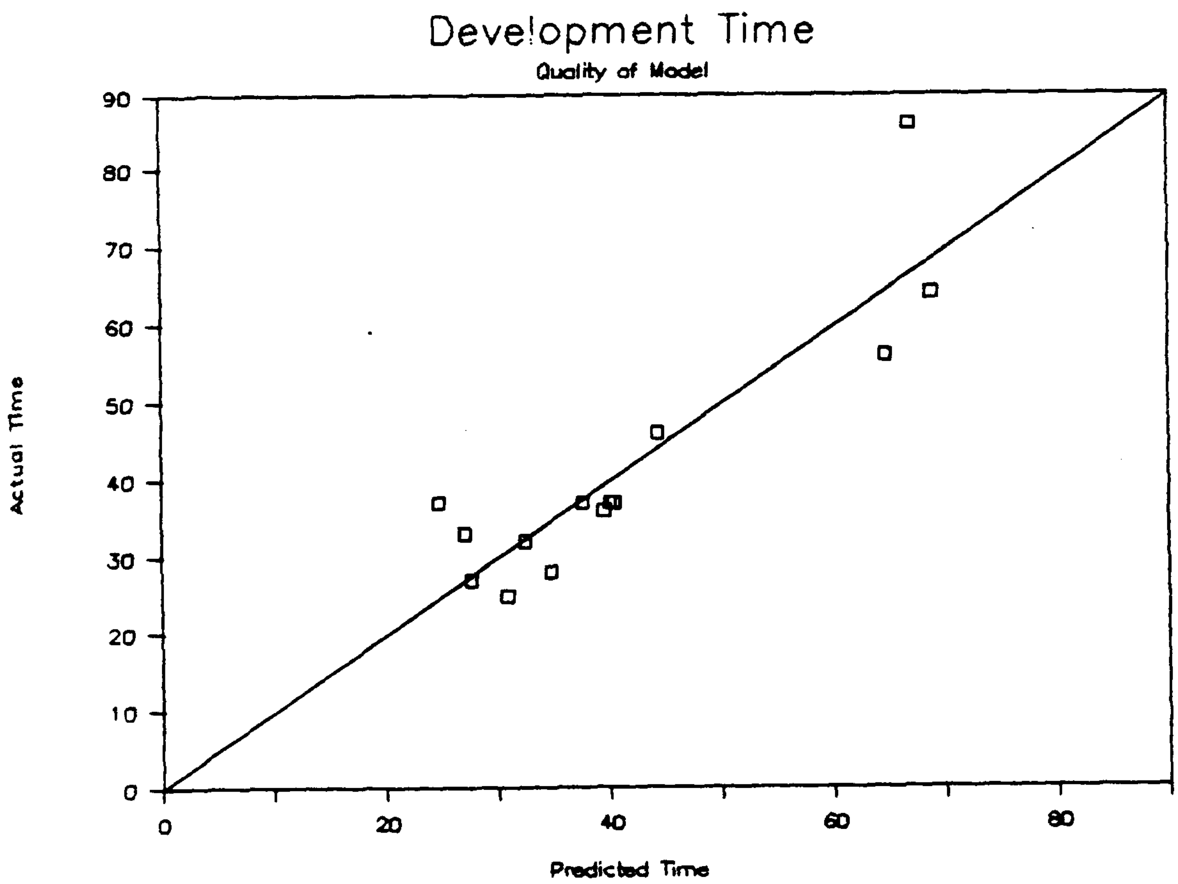


Figure 3.2 Predicted versus Actual Development Time

his Figure 3.[4] The implication is that there may be a "natural development time" for SOA extension projects.

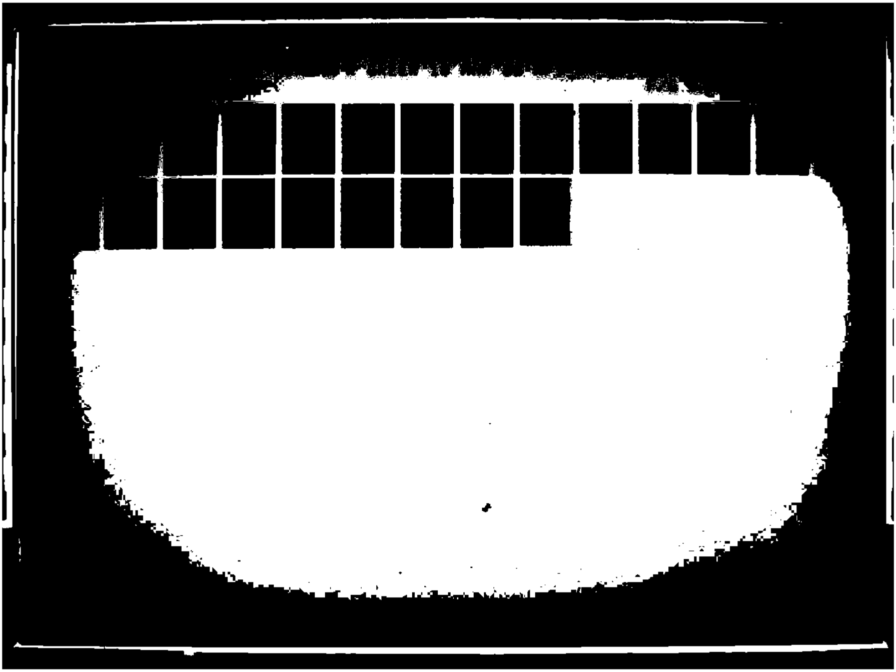
Figure 3. Adding more people doesn't speed up the process.

Figure 3.3 Putnam's Illustration

Now, take the <u>predicted</u> times from the above model as a "natural" time, and the <u>residuals</u> as departures (which may or may not have been planned <u>ex ante</u>) from this natural time. This suggests formulation of the following hypothesis:

H_2: Development Cost = f(Predicted time, Residual)

where Residual = Actual time - Predicted time.



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Test of Second Hypothesis

Again, the multiple regression produces good results,

Cost = - 61357 + 4793.1 Predicted Time + 7391.4 Residual		
t statistics	(3.12)	(2.47)
Significance	.004	.013
Variance explained (R^2)		.590
Adjusted R^2		.516
Standard error of the estimate		82647

A plot of predicted versus actual cost is shown below.

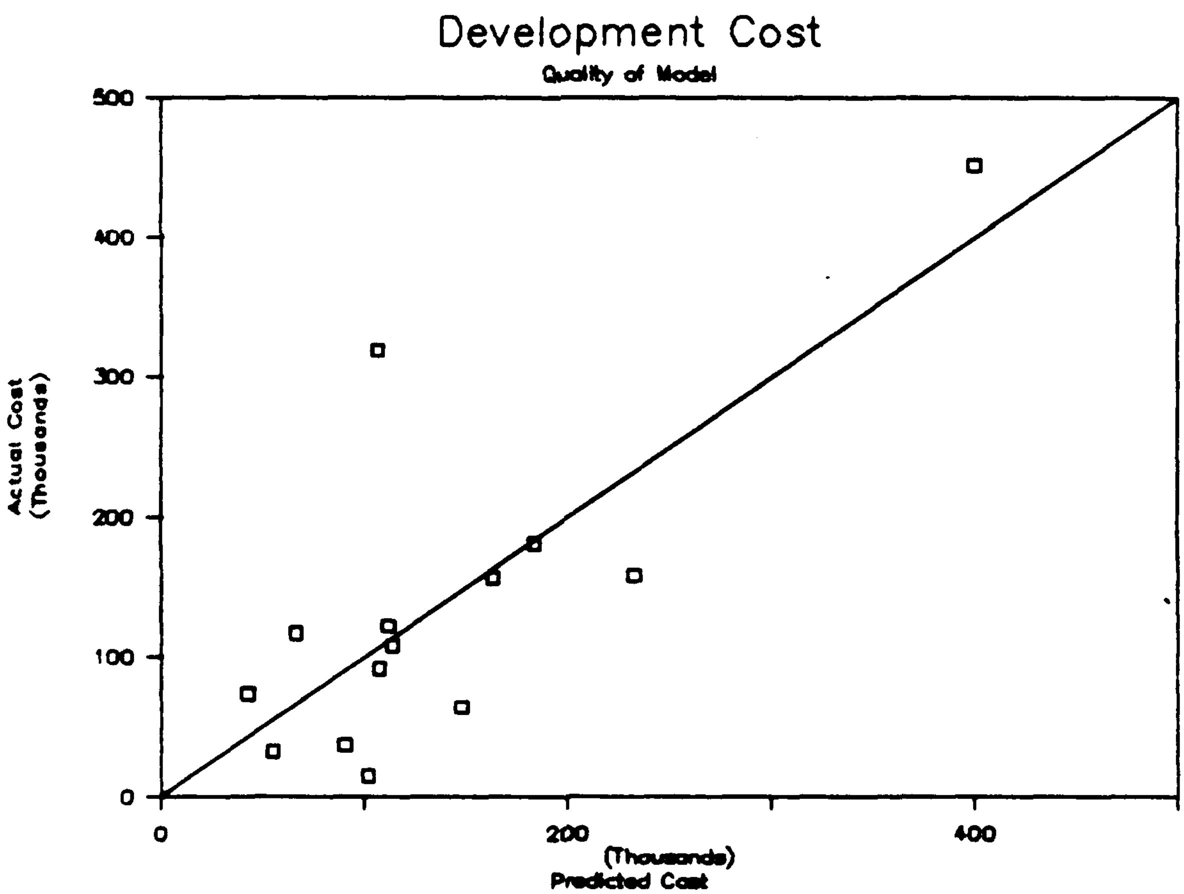


Figure 3.4 Predicted versus Actual Development Cost

INTERPRETATION OF RESULTS FOR CONTROL

The most basic principle of cost control is to attribute differences between expected costs and actual costs to causes. That is, to explain variances between predicted and actual costs. The preceding analysis affords us an opportunity to do exactly that.

Consider the information contained in Table 3.3 below. The column labeled "Ex Ante Cost Est" was constructed in the following way.

1. The particular system's values for Advance, Redesign and Reach (all determinable <u>ex ante</u>) were entered in the "Time" regression to predict a time that would be required for the system's development.

Table 3.3 Calculations for Performance Variances

System	Ex Ante Cost Est	Cost Est Based on Act Time	Variance Due to Time	Actual Cost	Cost Control Variance	Total Variance
H	86693.6	43171.8	-43521.8	73594.4	30422.6	-13099.2
O	71378.8	66256.4	-5122.4	116580.0	50323.6	45201.2
L	94692.3	90575.8	-4116.5	37228.4	-53347.4	-57463.9
J	105629.1	55081.5	-50547.6	32585.5	-22496.0	-73043.6
N	151593.0	163210.9	11617.9	155522.8	-7688.1	3929.8
M	132567.0	107001.7	-25565.2	319498.7	212497.0	186931.7
B	131031.5	107834.1	-23197.4	91707.4	-16126.7	-39324.1
Q	57540.8	147671.9	90131.1	64383.3	-83288.6	6842.5
P	68571.3	112126.8	43555.5	121932.3	9805.5	53361.0
E	119390.3	114144.5	-5245.8	108084.9	-6059.6	-11305.4
K	128438.5	101848.3	-26590.3	14943.2	-86905.1	-113495.3
R	249372.7	184120.6	-65252.1	180652.8	-3467.8	-68719.9
C	268926.2	232652.4	-36273.8	157820.4	-74832.0	-111105.8
I	259983.1	400111.4	140128.3	451274.0	51162.6	191290.9

2. The Predicted Time was input to the "Cost" regression, with the Residual set to zero (thereby assuming the predicted time will be achieved), to calculate the *ex ante* prediction of development cost.

Next the actual time for the project was compared to the predicted time to determine the Residual (*ex post*). The Cost regression was then revisited with values for both variables, and a new cost estimate constructed, considering the actual time residual for the project. This produced the "Cost Est Based on Act Time" column.

The difference between the *ex ante* cost estimate and the cost estimate based on the project's actual time has been termed the "Variance Due to Time". This figure is a best estimate of the portion of the total variance that can be attributed to the cost consequences of time delays (or to fortuitus and perhaps unforseen acceleration of the schedule). Minus figures are favorable, positive are unfavorable.

When Actual Cost is compared with the cost estimate based on actual time the result is a "Cost Control Variance". Given that the project actually took *t* time units to complete, the cost should have been "Cost Est Based on Act Time". The actual cost was a different amount, so the variation is attributed to cost control. Again, minus figures are favorable.

The variances identified above have been shown graphically in Figures 3.5 and 3.6 on pages 87 and 88. A graph of Total Cost Variance appears on page 89.

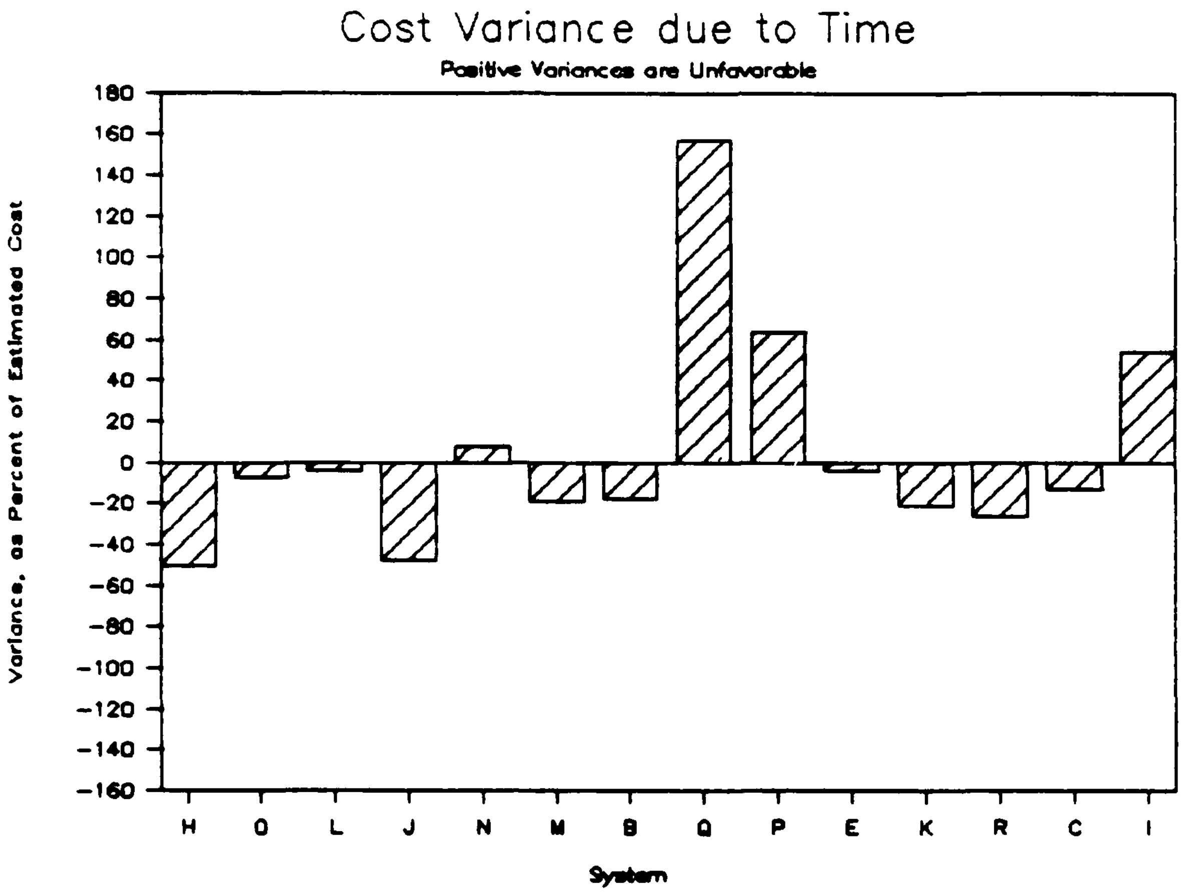


Figure 3.5 Time Variances for Satellite Development Cost

As Figure 3.7 indicates, there were significant unfavorable Total Cost Variances (expressed as a percent of estimated cost) for only four of the 14 programs. The cause of the variance in two of these cases, programs P and I, appears to be timing problems; in the other two cases, programs O and M, the origin of the problem seems to be cost control. (If these variances appear large compared with what the reader is accustomed to, consider the fact that there is far greater uncertainty surrounding a research project's costs than those of a routine manufacturing operation. Also, in fairness, consider the

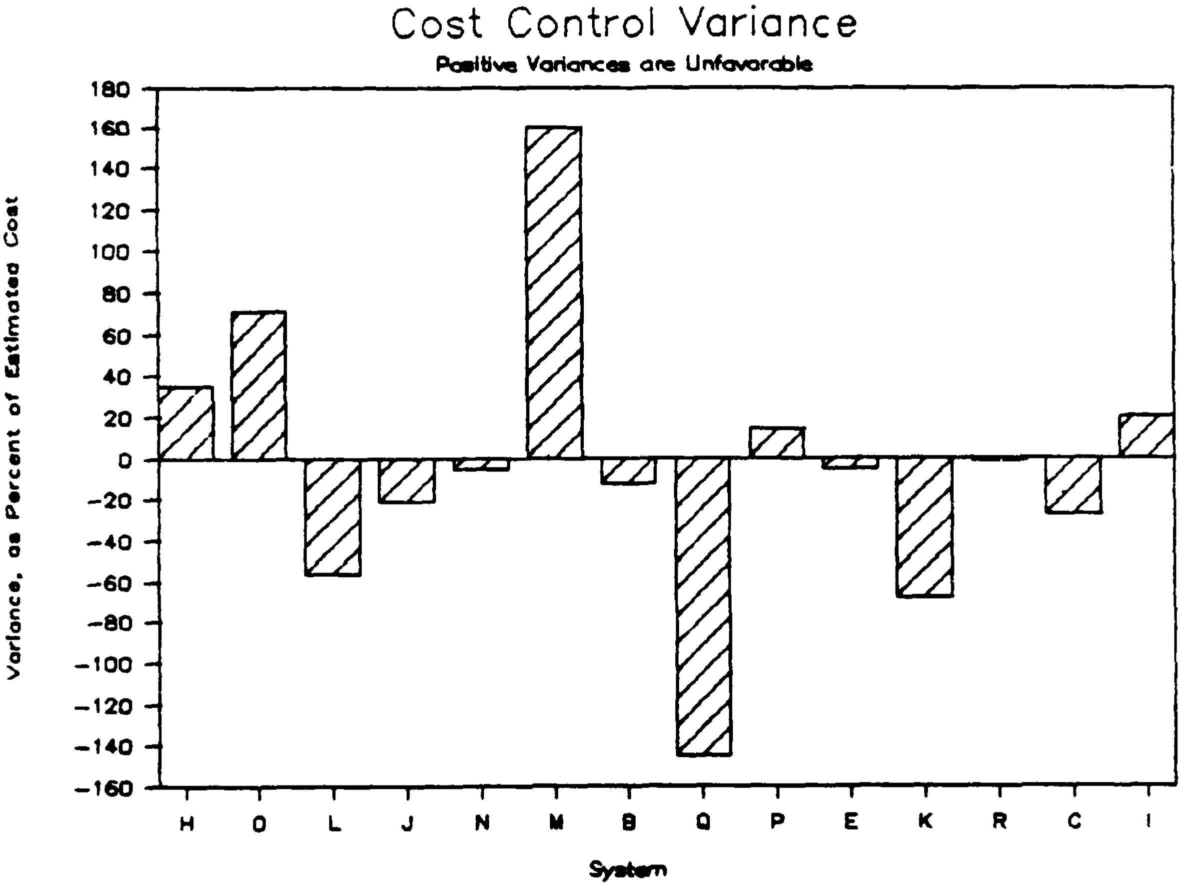


Figure 3.6 Cost Control Variances for Satellite Programs

imprecise nature of the data available for this study!)

Significant favorable Total Cost Variances were experienced in three cases, programs L, J and K. These pleasing results can be attributed to fortuitus timing in the case of Program J, and to excellent cost control in programs L and K.

Program Q had an interesting outcome; the time required for development was much greater than expected, so the cost variance due to time is large and unfavorable, but a very favorable cost control variance offset the timing effects--leaving the total cost variance insignificant.

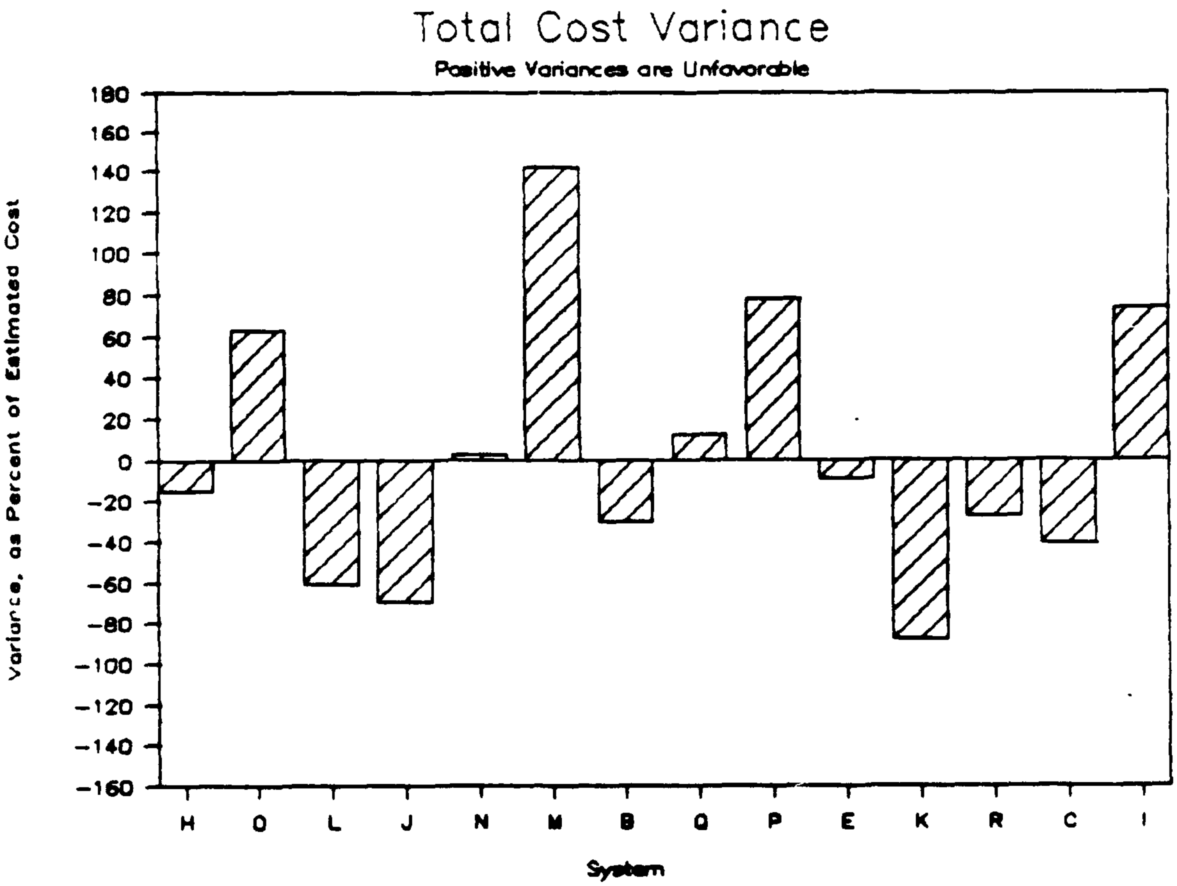


Figure 3.7 Total Cost Variances for Satellite Programs

CHAPTER SUMMARY

This chapter presented the fundamentals of estimating development cost, once the proper technology measures are known for the both the system under development and an appropriate base of predecessor systems. It has been shown that development time estimation is a critical intermediate step in this process.

In addition, methods for identifying and quantifying cost variances have been illustrated. This capability can provide information that may be useful for cost control.

ENDNOTES

1. See Dodson, E. N., "Measurement of State of the Art and Technological Advance," Technological Forecasting and Social Change, 27, (1985), pp. 129-146. The concept of a Technological Distance Score and the equation that follows are discussed on pp. 141-142.

2. Martino, J. P., "Measurement of Technology Using Tradeoff Surfaces," Technological Forecasting and Social Change, 27, (1985), 147-160. See especially pp. 153-157.

3. The model performs almost as well if the reach and redesign variables are omitted--R^2 drops only to 0.747 and the SEE rises to 8.786. The full model is retained because of its slightly better overall fit.

4. This illustration was taken from Putnam, L. H., Software Cost Estimating and Life-Cycle Control, The Institute of Electrical and Electronics Engineers, Inc., Computer Society Press, (1980), p. 99.

Chapter 4

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

When the various components of the Department of Defense (DoD) enter into contractual agreements calling for extensions of the State-of-the-Art (SOA), uncertainty generally requires that some variant of cost-plus contracting be employed. Therefore, it is important that DoD possess a highly developed ability to estimate the likely cost of achieving the desired technological advance.

This study examined the techniques currently available for costing SOA extension contracts by surveying the literature dealing explicitly with SOA measurement and costing. There was general recognition that the cost of an SOA extension relates to the scale of the undertaking. Most of the research that has been done to date therefore concentrates on measuring the amount of SOA extension represented by a sample set of efforts. SOA measurement strategies usually employ regression to combine design variables in an effort to produce a single measure of the SOA for a given system. The typical dependent variable is the "year of technology".

The relationship between the scale of an SOA extension and development cost has also been studied, but the findings from

these studies have been disappointing. Cost estimates made early in the life of a project have been plagued with error. The focus of this study has therefore been to develop a cost estimating model that is demonstrably workable for both prediction and cost control uses.

IMPORTANT BACKGROUND LITERATURE

Three prior works were found to be of pivotal importance. These were,

1. Dodson and Graver's development of the ellipsoid method for measuring the level of technology embodied in multifarious systems: the theoretical correctness of this model in its second-order form has been tested and demonstrated in many contemporary studies.[1]

2. Gordon and Munson's suggestion that factor analysis is an appropriate methodology for capturing the influence of a relatively large number of technological parameters: this method enables the analyst to avoid losing the influence of vital determinants of technology.[2]

3. Alexander and Nelson's definition of "technological continuity": their work demonstrated the need for using data for unbroken generations of systems when studying the methodologies for measuring SOA.[3]

The author's work drew heavily on the background laid by these three efforts. All were of great value.

THE MEASUREMENT OF TECHNOLOGY

Variable Selection

In selecting the variables to be used to measure the technology embedded in the systems to be studied, there is no substitute for expert judgement. Therefore, technical expertise must be sought, as it was in this study. In selecting variables, the experts must bear in mind that the SOA-determining characteristics must be at least partially influenced by the engineering development decisions. They should choose characteristics which are goals of the design process. In addition, the variables should be specified so that increasing values correspond to greater technical difficulty. Finally, the variable values should be ascertainable during the early decision-making stages of the system life-cycle.

The result of this process in the present study was identification of 18 variables or composite variables that could be used to describe satellite technology. These 18 variables were determinable for each of the 18 satellites in the sample (with one minor exception). In general, no more variables should be specified than there are systems in the data set. Said another way, there must be at least as many observations as there are relevant variables.

This procedure worked well. There was unclouded discussion and the results obtained represented consensus.

Factor Analysis

A factor analysis was then run. The data were found to be quite robust with high coefficients of variation and many significant correlations. In the final analysis, 11 variables were factored. They clustered very nicely onto four factors with 81.7% of the variance explained. The factors were easy to interpret.

The next step was to calculate factor scores for the systems. The factor scores are shown in Table 2.1 on page 59.

This process demonstrated that factor analysis does indeed provide a rigorous yet simple means for attaching considerable quantities of information to a very limited number (in this case, four) of variables.

The Ellipsoid Model

Dodson suggests that (in N-space) a new hypersurface is required for each SOA. In this study, however, only one ellipsoid was constructed for the entire sample. It can be thought of as an average technology hypersurface rather than a surface representing one static SOA.[4]

Note that the factor scores themselves represent particular blends of the parameters affecting the level of system technology. The technology measure, the radial distance from the origin, is a function of the four scores.

There is no statistically rigorous methodology for determining adequate sample sizes in ellipsoid construction. However, the author's experience has led him to believe that reasonable stability is usually achieved when the number of observations in the sample is at least four times the number of variables per observation. This rule of thumb is recommended as a guideline. Subject to this guideline, the method works well in providing system SOA measures.

COST ESTIMATION AND CONTROL

The end purpose of developing SOA measures is to facilitate prediction of the cost of developing new technological systems, which is a necessary initial step in any attempt to control such costs. It was therefore necessary to search for statistical associations between (1) the degree to which a system's technology has been extended, and (2) the level of activity required to bring these extensions about.

More Precise Measurement

The definition of the change represented by a particular technological development required careful consideration. This led to better articulation of the concept of an SOA extension.

The technological objective of the project and the closest existing technology were used to identify the development task by

referencing the technological distance separating the two.5 This is the Euclidian distance between the two points.

Several more detailed measurement concepts were then developed. There are three: reach, advance and redesign. The reach measures the total technological complexity, or the overall ambition of the project. Advance represents the "invention" aspects of the development--the "true" SOA progress required. The redesign portion represents a movement parallel to an old SOA surface.

Testing the Time Hypothesis

The first hypothesis tested was that the difficulty of the development task, as measured by the time required for its completion, is a function of the three measures of technological spread. The result was,

$$\text{Time} = 52.86 + 218.93\ \text{Advance} - 34.28\ \text{Redesign} - 17.37\ \text{Reach}$$

	Advance	Redesign	Reach
t statistics	(3.69)	(1.45)	(0.47)
Significance	.001	.085	.322

Variance explained (R^2)	.791
Adjusted R^2	.728
Standard error of the estimate	8.745

The regression is highly significant. Advance is by far the most important determinant of development time. Neither redesign nor reach is statistically significant.

Cost Prediction Hypothesis

It was hypothesized that development cost is not a smooth function of development time. If a program drags on beyond its intended completion date, it becomes relatively more costly to compress the required accomplishment into an increasingly abbreviated time horizon. This suggests that there is a "natural" project time, and that the residuals from this natural time may influence cost. Again, the multiple regression produced good results,

Cost = - 61357 +	4793.1 Predicted Time +	7391.4 Residual
t statistics	(3.12)	(2.47)
Significance	.004	.013
Variance explained (R^2)		.590
Adjusted R^2		.516
Standard error of the estimate		82647

Cost Control

The most basic task in cost control is to explain variances between predicted and actual costs. The regressions developed earlier provided a basis for doing so.

First, Advance, Redesign and Reach were used in the "Time" regression to predict the time that would be required for the system's development. Then the Predicted Time was input to the "Cost" regression (with the Residual set to zero) to provide an

ex ante prediction of development cost.

Next the *actual* time for the project was compared to the predicted time to determine the Residual. The Cost regression was then used again--this time to calculate a new cost estimate considering the residual time for the project. The difference between the *ex ante* cost estimate and the cost estimate based on the project's actual time is the "Variance Due to Time"--the portion of the total variance that can be attributed to the cost consequences of time delays.

Actual Cost is compared with the cost estimate based on actual time to determine a "Cost Control Variance". This variance indicates the quality of cost control for the project.

CONCLUSIONS

The fundamentals developed in this study provide a workable methodology for measuring the level of technology embodied in complex systems, and for measuring the degree of advance represented by the technological characteristics of new systems compared with old. When a continuous data base is available, the methods in this study have also been shown to be effective in relating SOA advance to development cost. This capability can provide information that may be useful for cost control.

The requisite data used in implementing this procedure have a great deal to do with the quality of the results achieved. If the benefits of good cost control are to be obtained it is

absolutely essential to have a relevant and complete data base. Let us now turn to a description of the data requirements.

Data Requirements

1. Data must be of sufficient quantity. It is necessary to have at least four valid observations (systems) in the data base for every factor that is identified through the factor analysis procedure. More observations help to provide stability in constructing the ellipsoid. The data base must contain no fewer than 16-20 valid systems.

2. The number and quality of variables describing the technology in each system must be sufficient to allow experts to construct a reasonably complete menu of design objectives. In this study there were 85 variables: the engineers condensed this list to 18.

3. Reliable development cost and time data must be available. Cost figures must be dated for price-level adjusting and development times must be recorded. There is currently no reliable methodology for cost estimating that does not make use of development time.

4. The size and continuity of a data base can be improved by recording at the sub-system rather than system level. For example, missile and torpedo guidance systems may be evolutions of one another. By recording data for guidance systems rather than for torpedoes the quality of a data base is improved.

RECOMMENDATIONS

Inasmuch as the cost control objectives are worthwhile and the research methodology has been shown to perform, it would seem desirable to attempt applications in settings other than satellite development. The principal difficulty encountered in doing so will undoubtedly be the availability of data. The most significant recommendation that could be made, therefore, is that serious efforts be made to create and maintain relevant data bases on major systems that are expected to be advanced beyond their present SOA. The data should include technical information as well as cost and development time details.

Of course, the methodology developed here can be improved, and it is recommended that efforts continue in that direction. Two additional arenas for study come to mind--aircraft and electronics. A study of aircraft development cost could be pursued with the cooperation of a large manufacturer. Electronics would require more industry-wide representation, so would be a more difficult undertaking.

Finally, the financial and operating characteristics of contractors who have enjoyed unusual success in cost control may be detectable. If so, this information could be extravagantly useful in identifying and choosing among alternate sources for new systems. The potential savings would be so large that this question is clearly worth investigating.

ENDNOTES

1. See Dodson, E. N., "A General Approach to Measurement of the State of the Art and Technological Advance," Technological Forecasting, 1 (1970), pp. 391-408. The issue of "theoretical correctness" is demonstrated by the method's compliance with Grosch's Law. See Knight, K. E., "A Functional and Structural Measurement of Technology," Technological Forecasting and Social Change, 27 (1985), pp. 107-127.

2. See Gordon, T. J., and T. R. Munson, "A Proposed Convention for Measuring the State of the Art of Products or Processes," Technological Forecasting and Social Change, 20 (1981), pp. 1-26.

3. Alexander, A. J., and J. R. Nelson, "Measuring Technological Change: Aircraft Turbine Engines," Report No. R-1017-ARPA/PR, The RAND Corporation, (Santa Monica, June, 1972), 37 pgs.

4. Bear in mind that the only purpose of the ellipsoid is to attach relative distance-from-the-origin values to the various systems in the sample. In any case, this representation is allowable as a result of the assumption of continuity. See Alexander and Nelson, op. cit.

5. See Dodson, E. N., "Measurement of State of the Art and Technological Advance," Technological Forecasting and Social Change, 27, (1985), pp. 129-146. The concept of a Technological Distance Score is discussed on pp. 141-142.

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